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INVESTIGATION OF THE MECHANICS OF CARGO HANDLING BY AERIAL CRANE-TYPE AIRCRAFT

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THE BOEING COMPANY
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A requirement for an analysis of problems that may be encountered in the external transporting of cargo by aerial crane-type helicopters in the 12- to 20-ton payload range and the establishment of possible solutions to these problems form the basis for this study. The conclusions drawn by the contractor are arrived at through a thorough and systematic effort and, where appropriate, are under evaluation by this activity. It is the opinion of this activity that the design parameters contained in this report are satisfactory for use in hoist-system design studies.

Future work to be conducted by this activity relative to this area includes a design study for a 20-ton external load-handling system, involving a parametric analysis of single-point plus two-point and a single-point plus four-point suspension arrangement. Results of this design study will form the basis for the detail design, fabrication, and test of an experimental system in the future.

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INVESTIGATION OF THE MECHANICS
OF CARGO HANDLING BY AERIAL
CRANE-TYPE AIRCRAFT

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by

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Prepared by
VERTOL DIVISION
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Morton, Pennsylvania

for
U.S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

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FOREWORD

Acknowledgment is made to the following organizations for their assistance in permitting the use of certain illustrations in this report:

Air Progress Magazine, New York, New York

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Michigan

SUMMARY

This report covers a study of helicopter external cargo handling systems conducted by the Vertol Division of The Boeing Company under Contract DA 44-177-AMC-312(T).

The major part of the work consisted of an analytical study of airborne hoist systems, which included comparison of load acquisition techniques, crane-type long landing gears, and single- and multi-point suspension systems. Other aspects were also investigated, such as personnel safety, hoist system feasibility and reliability, and basic helicopter stability, as well as the overall feasibility, efficiency, and reliability of concepts for handling external cargo by crane-type helicopters.

One new approach to airborne hoist systems is proposed in the form of a two-point hoist with a connecting beam. A two-point system allows lifting of single and multiple loads; it may also be configured to provide a single-point hoist. Only two identical winches are required compared to the five winches of two different capacities included in current systems. Also, techniques may be developed to ensure complete, synchronized release of the load by both electrical and mechanical means.

A comparison of various load acquisition methods indicates that, for short-range missions, hovering load acquisition is the most effective technique. For long-range missions, however, in which loads are rigidly restrained to the fuselage (as in the case of pods) or tied down to platforms, the taxi-over-the-load method is better.

For transporting external loads, crane or long-landing-gear helicopters offer some advantages in cruising speed and range over transport helicopters because of the ability of the former to handle the loads in podded or platform-mounted form. Against this must be weighed the greater mission flexibility of transport-type aircraft.

The vertical bounce phenomenon was analyzed and found to be dependent on inputs to the thrust control system provided by the pilot. An external load is not essential to system excitation, but the condition is aggravated by it. Minimization of

inadvertent pilot inputs to the control loop will avoid this excitation. Changes to control system sensitivity and damping are suggested as a partial solution to the problem. The effect of the external load in the vertical condition can be minimized by a load isolator.

Hover stability analysis shows little difference between single-, two-, and four-point suspension. Stability deteriorates with increased suspension lengths, becoming mildly unstable at 80 feet. The distance between the suspension attachment and the aircraft cg was shown to have a powerful effect on stability. Ideally, this distance would be zero; stability deteriorates rapidly when the distance exceeds 5 feet. Hover instabilities are basically of long period and are amenable to automatic stabilization.

The stability of the helicopter in forward flight was analyzed for neutrally stable slung loads. The results indicate that the load and suspension type have little effect on the basic helicopter stability. Forward speed stability and control limitations are usually due to the effects of load aerodynamic instability on the handling qualities of the helicopter.

For aerodynamically unstable loads, multi-point suspension allows a significant increase in forward speed over single-point suspension; four-point is only slightly better than two-point suspension.

A test plan describing equipment and associated items required to quantify and qualify the defined design parameters is included.

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SYMBOLS

<u>Symbol</u>	<u>Definition</u>	<u>Unit</u>
a	Half distance between sling legs on cargo ring	ft
A	Rotor disc area	ft ²
B	Half longitudinal distance between sling legs at the load	ft
C	Half lateral distance between sling legs at the load (four-point suspension)	ft
C _d	Aerodynamic drag coefficient	
C _l	Aerodynamic lift coefficient of load	
C _m	Aerodynamic yawing moment coefficient	
D	Load aerodynamic drag	lb
f	Frequency	cps
f _r	Resonant frequency	cps
g	Acceleration due to gravity	32.2 ft/sec ²
h	Height of sling from load to pendant	ft
H	Height of sling	ft
I	Load yaw inertia	slug-ft ²
k	Soil modulus	lb/in ²⁺ⁿ
k _a	Effective stiffness of pilot's arm	lb/ft
k _s	Stiffness of pilot's seat	lb/ft
k _T	Stick sensitivity (pounds of thrust per foot of control stick deflection)	

<u>Symbol</u>	<u>Definition</u>	<u>Unit</u>
K	Strouhal number	
K ₁	Load isolator spring rate	lb/in.
K ₂	Sling spring rate	lb/in.
K _R	Resultant spring rate	lb/in.
l	Body length	ft
L	Aerodynamic lift of load	lb
L _e	Element length	ft
L'	Characteristic width of element	ft
m	External load mass	slugs
m _a	Effective control mass	slug-ft ²
m _f	Effective mass of fuselage	slug-ft ²
m _p	Effective mass of pilot	slug-ft ²
M	Yawing moment of the load	ft-lb
M _R	Rotor hub rolling moment	ft-lb
n	Soil exponent	
N	Any integer (1,2,3....)	
q	Dynamic pressure	lb/ft ²
R	Resistance to motion	lb
R ₀	Standard motion-resistance factor used to nondimensionalize motion resistance	
S	Body frontal area	ft ²
t	Time	sec

<u>Symbol</u>	<u>Distribution</u>	<u>Unit</u>
T	Rotor thrust	lb
T _s	Tension	lb
T _ψ	Suspension system aligning torque	ft-lb
u	Height of rotor from cg	ft
v	Flight speed	ft/sec
v _i	Induced velocity at rotor disc	ft/sec
w _s	Weight per unit length	lb
w	Height of cg from ground	ft
W	Weight of external load	lb
W _H	Helicopter weight	lb
X _f	Defined in Figure 94	
X _p	Defined in Figure 94	
α	Angle of attack of load	rad
β	Rotor disc lateral tilt angle	rad
γ	Suspension geometric variable (defined in Figure 35)	
δ	Stick cg offset	ft
η	Real axis of the root locus plane	
θ	Suspension geometric variable (defined in Figure 35)	
ρ	Air density	slug/ft ³
τ	Feedback time delay	sec
φ	Helicopter roll angle	rad

<u>Symbol</u>	<u>Definition</u>	<u>Unit</u>
ψ	Yaw angle	rad
Ω	Rotor rotational speed	rad/sec
ω	Natural frequency	rad/sec
ω_a	$\sqrt{\frac{k_a}{m_a}}$	rad/sec
ω_e	Load vertical vibration frequency	rad/sec
ω_I	Load isolator natural frequency	rad/sec
ω_ℓ	Lateral or longitudinal pendulum frequency	rad/sec
ω_N	Resultant natural frequency	rad/sec
ω_s	Pilot's seat frequency	rad/sec
ω_T	$\sqrt{\frac{k_T}{m_f}}$	
ω_τ	Feedback phase angle corresponding to the τ delay time	rad

<u>Symbol</u>	<u>Definition</u>	<u>Unit</u>
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ω_N	Resultant natural frequency	rad/sec
ω_s	Pilot's seat frequency	rad/sec
ω_T	$\sqrt{\frac{k_T}{m_f}}$	
$\omega\tau$	Feedback phase angle corresponding to the τ delay time	rad

INTRODUCTION

The introduction of military helicopters with lift capacities of 2000 to 3000 pounds led to recognition of the value of external lifting techniques for delivery of bulky loads to forward areas. Helicopter performance in this role was adequately demonstrated during the Korean Conflict, where supply feats were performed which would have been impossible by other means. The experience gained in Korea laid the foundation for new generations of transport helicopters with lift capacities up to a present maximum of 20,000 pounds.

The cargo hook has proved to be an invaluable addition to the transport helicopter's capability. All modern transports are equipped with cargo hooks, including the Army's standard medium transport, the CH-47A Chinook, shown transporting a damaged aircraft in Figure 1.

Interest in the gains to be made by configuring an aircraft purely for the external load mission led to the S-60 helicopter and subsequently to the CH-54A Flying Crane, shown in Figure 2.

Cargo handling techniques have developed in an evolutionary manner to the current state of the art. Interest by the Army in a heavy-lift helicopter with a lift capacity of between 12 and 20 tons required that cargo handling techniques for external loads be re-evaluated. This interest led to Request for Proposal, No. AMC-44-177-65, from USAAVLABS to perform a study of the mechanics of cargo handling by aerial crane-type aircraft, and to the subsequent award of a contract for such a study to The Boeing Company Vertol Division. This report covers the results of an interface subsystem configuration analysis and defines test plans to investigate problems and their solutions as uncovered in the course of this analysis.

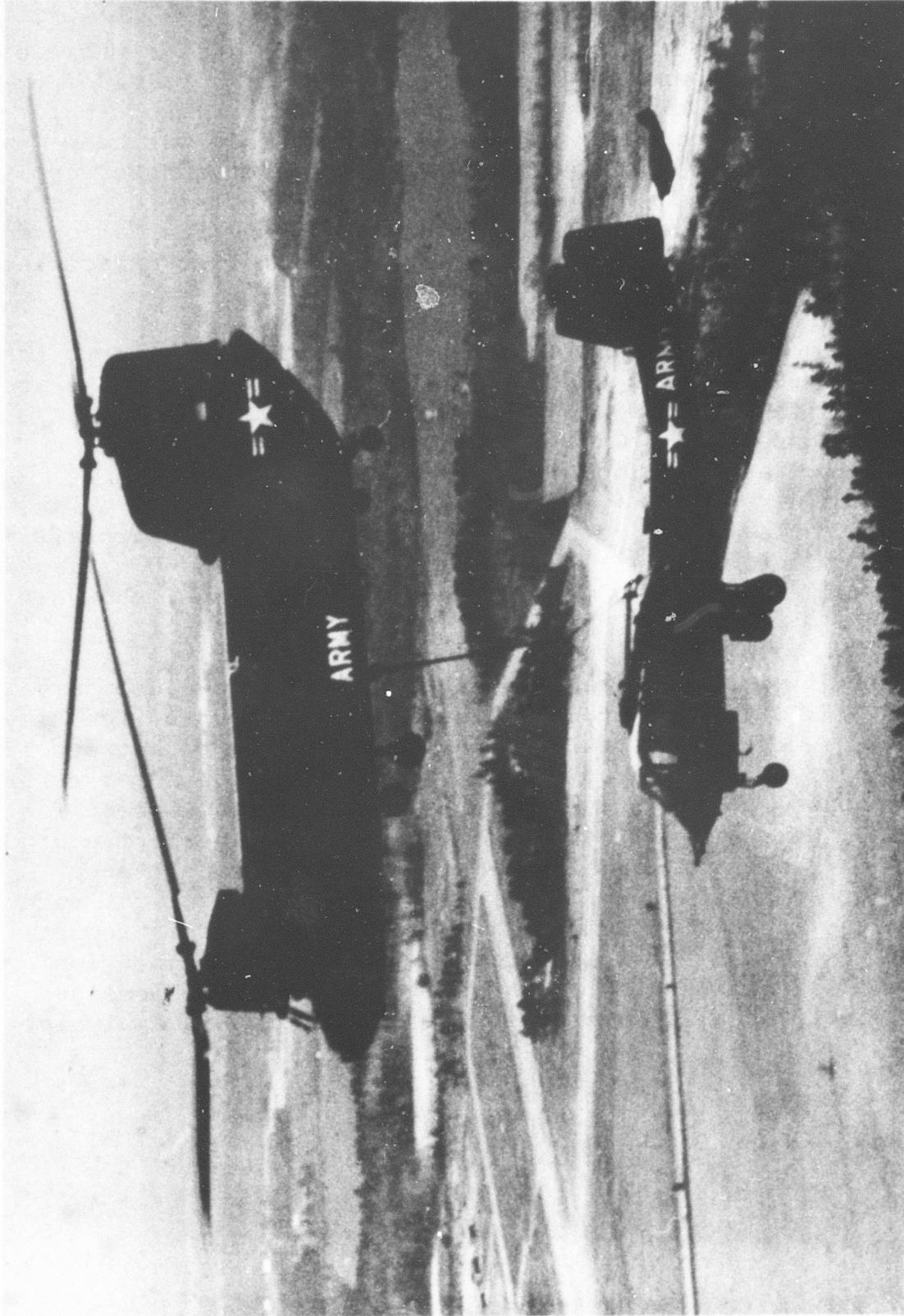


Figure 1. A CH-47A Shown Recovering a Disabled Aircraft

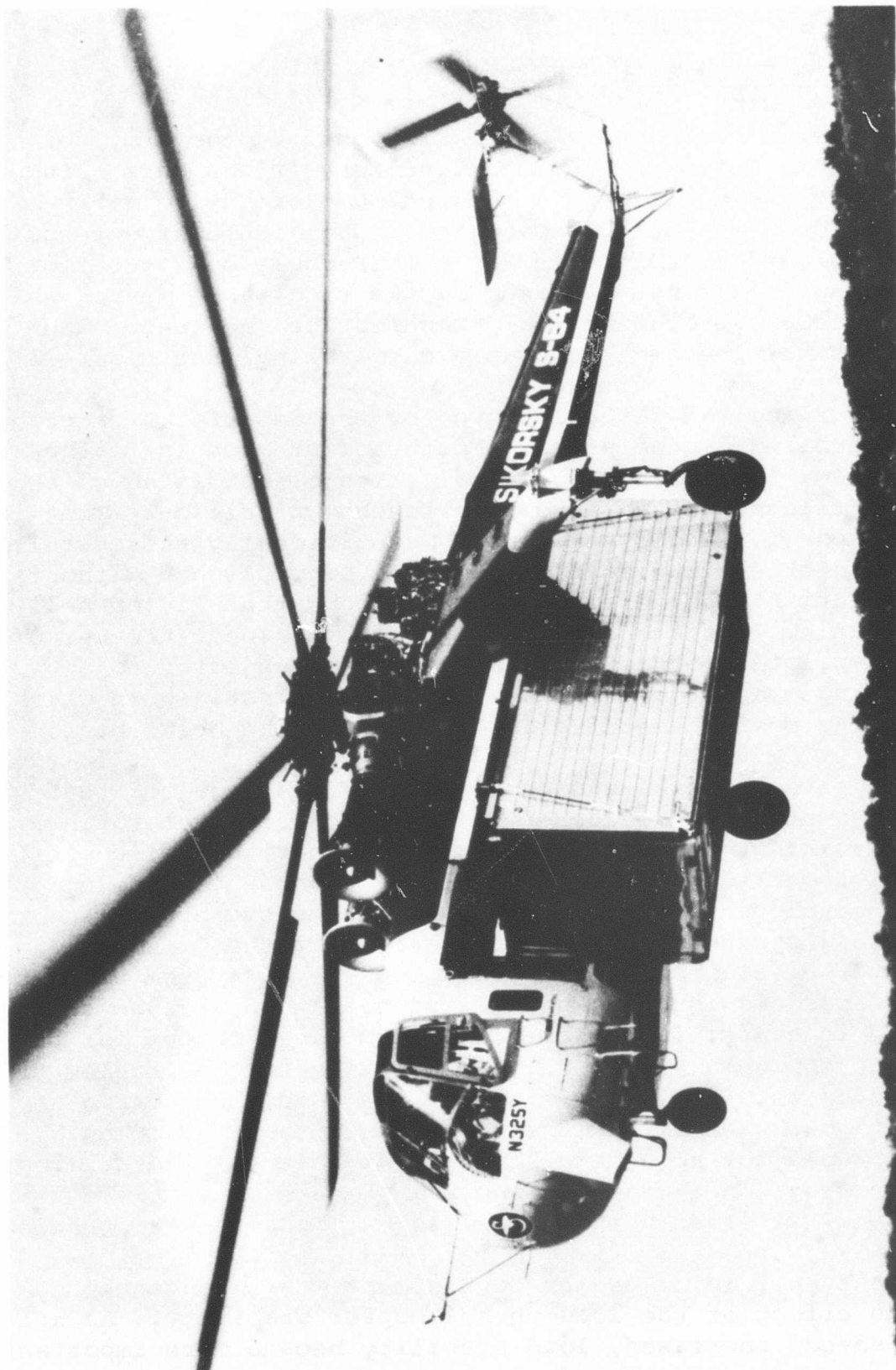


Figure 2. A CH-54A Skycrane

LOAD SUSPENSION SYSTEMS

EVOLUTION OF SUSPENSION SYSTEMS

Although cargo helicopters were being used by the Army for several years before the Korean Conflict, it was during this action that the helicopter's inherent capability to carry external loads was fully recognized. The method of external suspension used at that time was a four-cable configuration terminating at a ring. Affixed to the ring was a device which allowed manual attachment and detachment of the load. The entire assembly became known as a cargo sling (see Figure 3).

The cargo sling was later improved by the addition of a cargo hook controlled by the pilot. Further improvements to the hook system, in addition to manual release, consisted of an electric release and an automatic touchdown release. The improved cargo sling system proved conditionally successful; it was essential that load lift-off be accomplished without sideways drift. For example, it was found that if the helicopter was not positioned directly over the load (because of drift or pilot error), the helicopter was subjected to an overturning moment. Figure 4 exhibits one instance in which overturning moment resulted in the loss of the helicopter.

It was apparent that a suspension system was required that would prevent load-helicopter misalignment from generating any overturning moments which would endanger the helicopter. To resolve overturning, the Vertol Division of The Boeing Company developed and built, under Government contract, a cargo swing system which eliminated the effects of load-helicopter misalignment. However, because of system complexity, the cargo swing, shown in Figures 5 and 6, was never produced in quantity. A similar system was produced for the CH-34, as shown in Figure 7. The solution to the problem of overturning was, basically, to keep the load line acting always through the aircraft cg, to ensure that any moment created would not be a danger to flight safety. The helicopter load-carrying configurations shown in Figures 8 and 9 effectively resolved the load-helicopter misalignment problem.

Subsequent helicopter design development was also concerned with the effect of the load on helicopter stability. As helicopter speeds increased, load stability became more important, and various arrangements of slings and suspension systems were

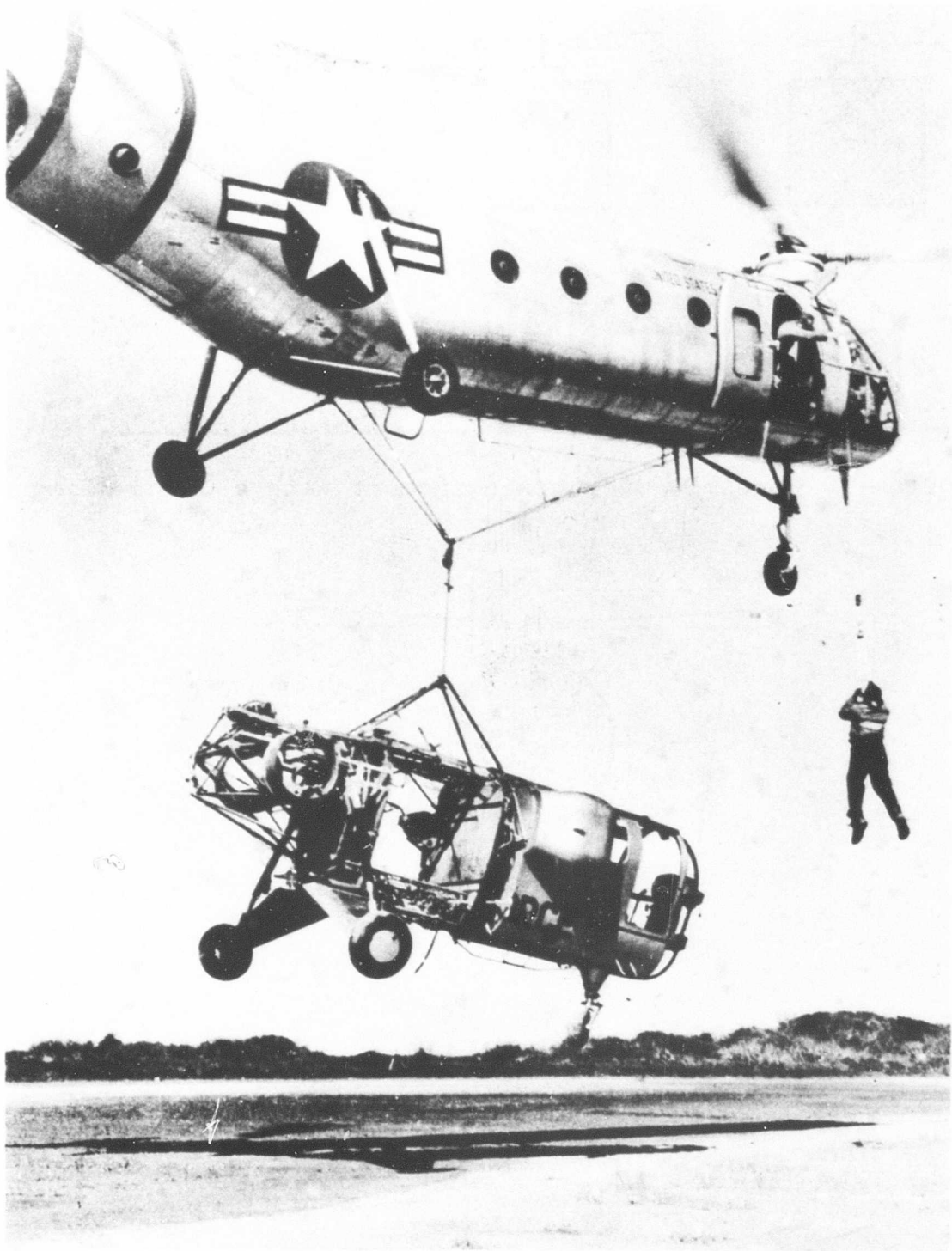


Figure 3. CH-21 with a Cargo Sling

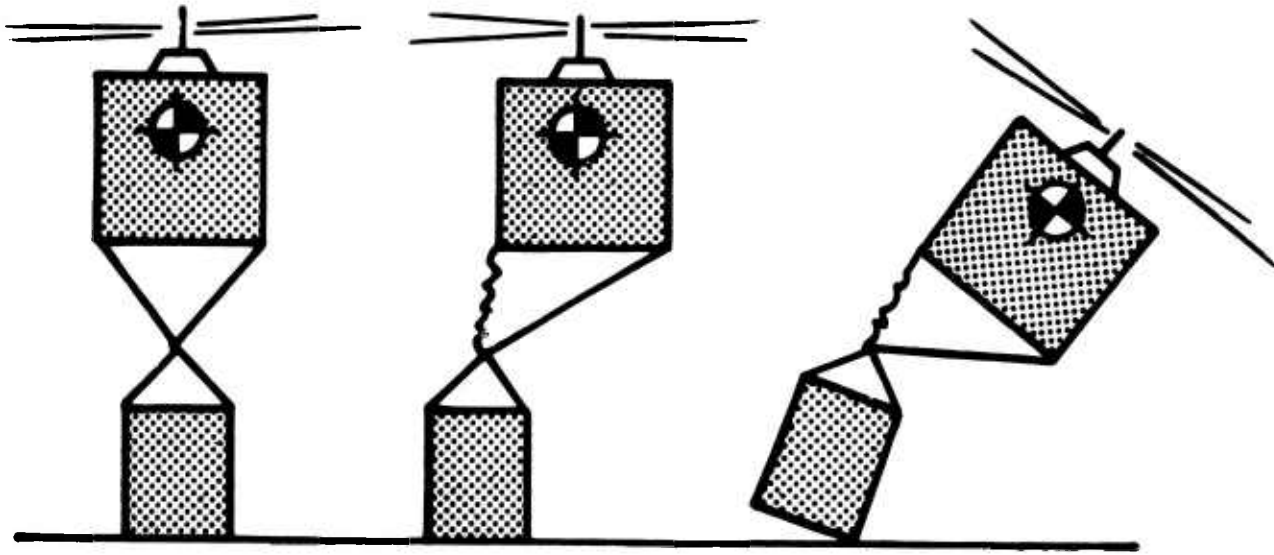


Figure 4. Possible Overturning Moment with a Cargo Sling

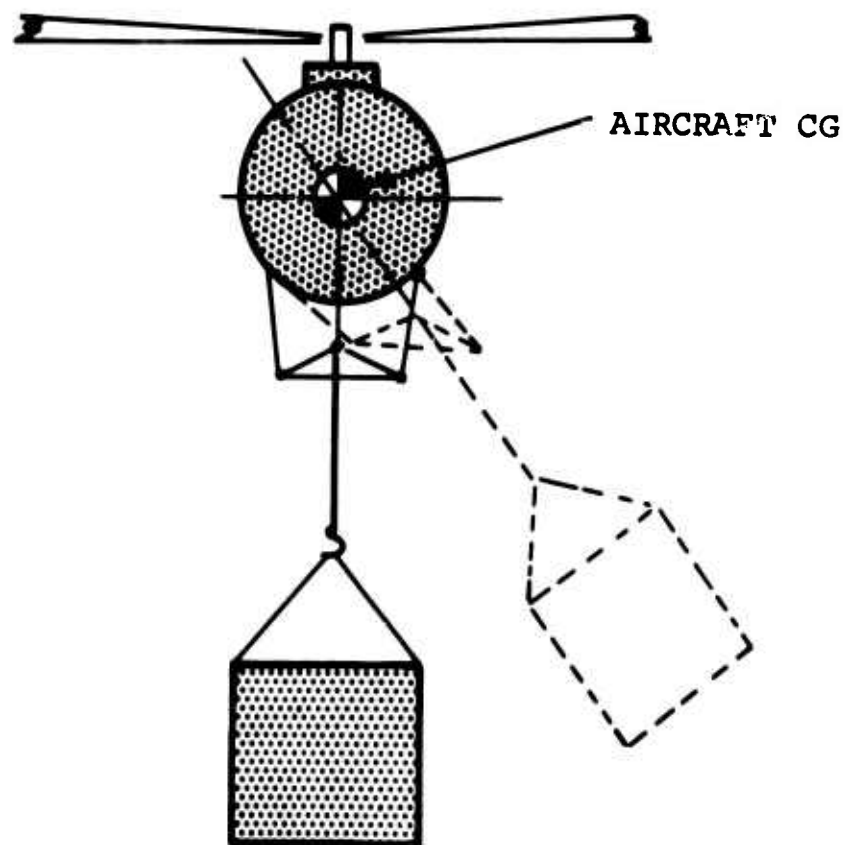


Figure 5. Cargo Swing

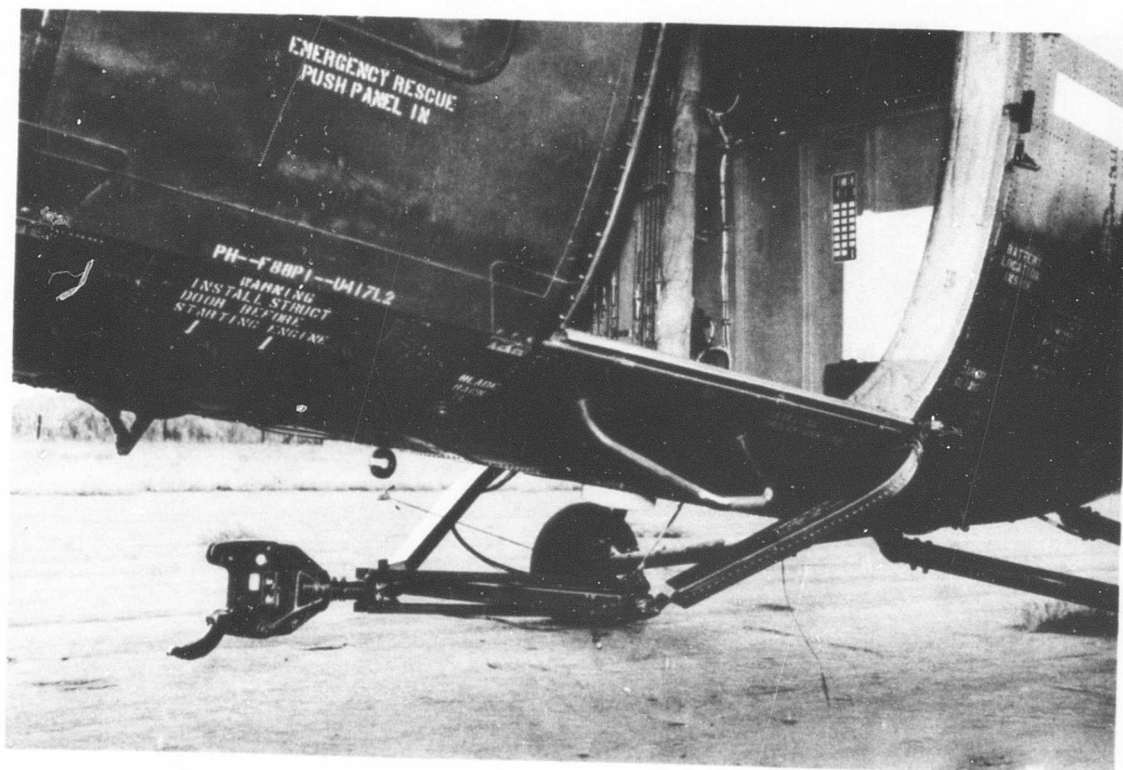


Figure 6. CH-21 Cargo Swing

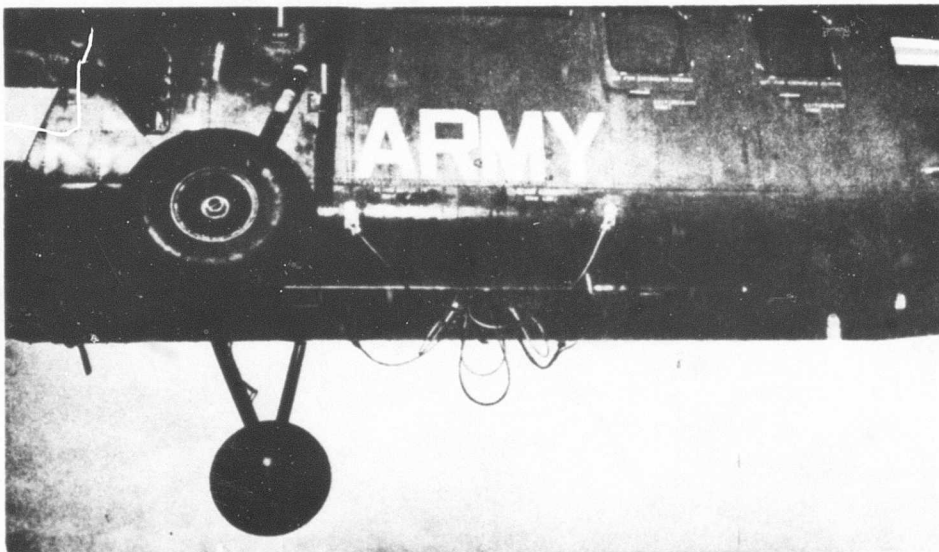
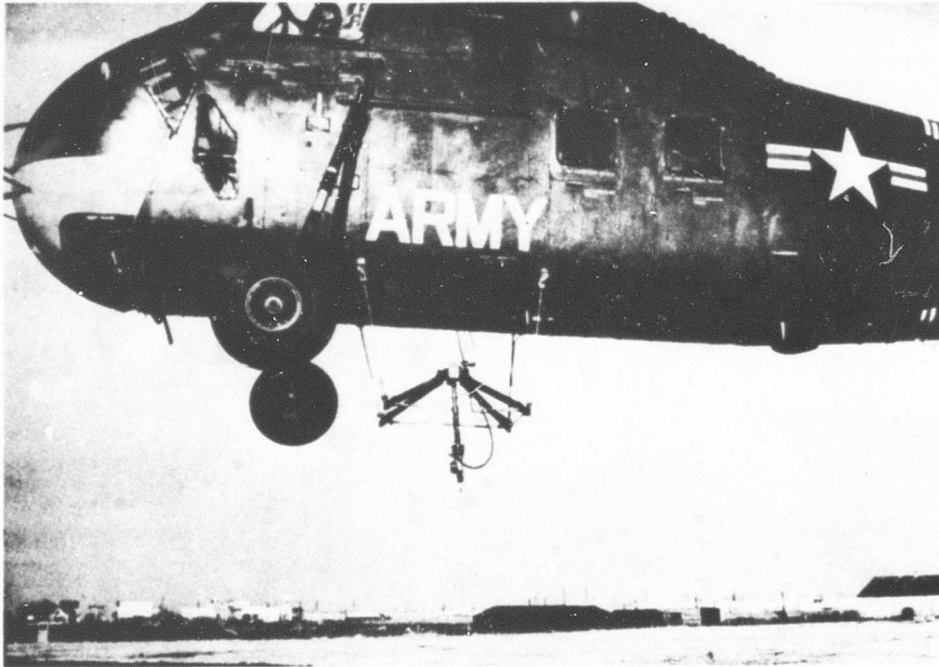


Figure 7. CH-34 Cargo Swing

evolved to effect a solution. Figure 10 shows an armored self-propelled weapon being transported by a CH-54A. The load is suspended by a four-point pickup arrangement, attached to the aircraft by a complex arrangement of slings which control the fore and aft pitch and the yaw motions of the load.

Load stability is discussed in detail in this section under STABILITY OF SLUNG LOADS; helicopter stability is discussed under the heading STABILITY IN HOVER AND FORWARD FLIGHT.

Another design development introduced winching of loads up and down from a helicopter while in hover. This important additional capability permitted the lifting and lowering of materiel in areas where a helicopter was incapable of landing (e.g., forest or rocky terrain). Refer to the HOIST SYSTEMS section.

CARGO HOOKS

Cargo hooks presently in use on external cargo handling systems have been developed from the original hook introduced on the H-34 and H-21 helicopters during the 1950's. This original hook, see Figure 11, was suspended from a fixed sling system and released manually, by means of a drawstring, by the airborne crew chief or by ground personnel. Further development of cargo hooks introduced an electromechanical remote load-release controlled by the pilot. Since electrical malfunction was possible, the manual release system was retained. Other hook refinements included automatic recocking of the hook after cargo release, and automatic touchdown release. Hooks of this type were built for the H-21 and H-34 helicopters (see Figure 12).

Touchdown Release

Ordinarily, upon delivery, a slung load is released by a mechanism which automatically opens the cargo hook when the weight of the cargo is transferred to the ground, eliminating the need for ground personnel to release the cargo. Touchdown release hooks have been designed with capacities up to 25,000 pounds. Such designs incorporate safety features which prevent hook opening in flight as a result of momentary release of sling tension in turbulent air, and other inadvertent release. Touchdown hook designs also include a jettisoning feature which permits crew members to drop the cargo should the helicopter be endangered by engine failure or other emergencies, such as failure of the touchdown release mechanism to operate.

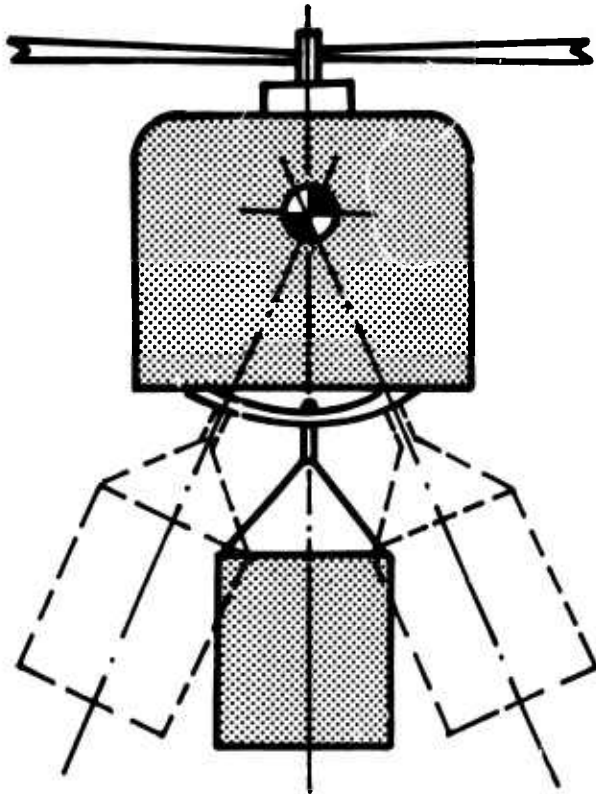


Figure 8. CH-47A Cargo Beam

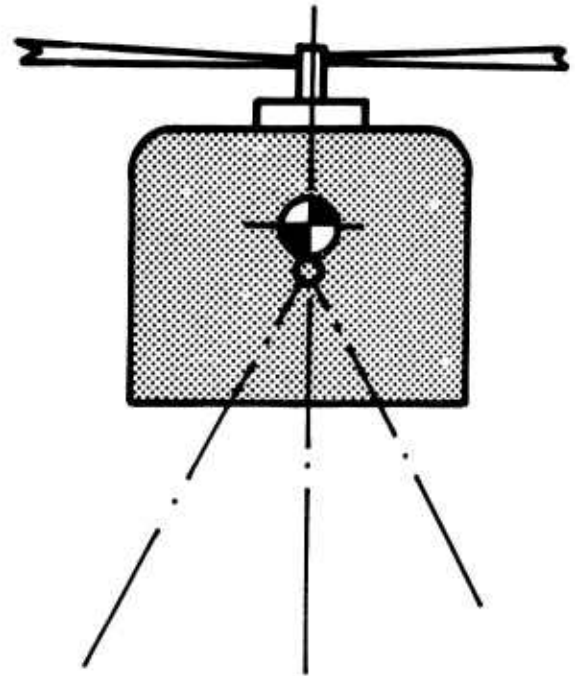


Figure 9. CH-54A, Load Suspended Near CG

Cargo Hooks on Hoist Systems

The use of cargo hooks on hoist systems imposes the complexity of connecting the release devices through the hoist system or parallel to it. In electrically released hooks, electrical conductors must either pass through the hoist cable or run parallel to it, the latter system requiring an additional take-up spool. Passing the electrical conductor through the hoist cable is the most commonly used method; this, however, presents a number of serious drawbacks. When the conductors pass through the cable which in turn runs around the winch drum, it is necessary to use slip rings to supply voltage to the conductors. Slip rings are considered to be low-life, low-reliability items. Also, electrical conductors built into the core of flexible cables are subject to crushing loads when the cable is in tension and, more particularly, when it is wound around the winch drum. Furthermore, repeated winding on and off the drum creates fatigue in the conductors.



Figure 10 . Multi-Point Suspension of Armored Vehicle

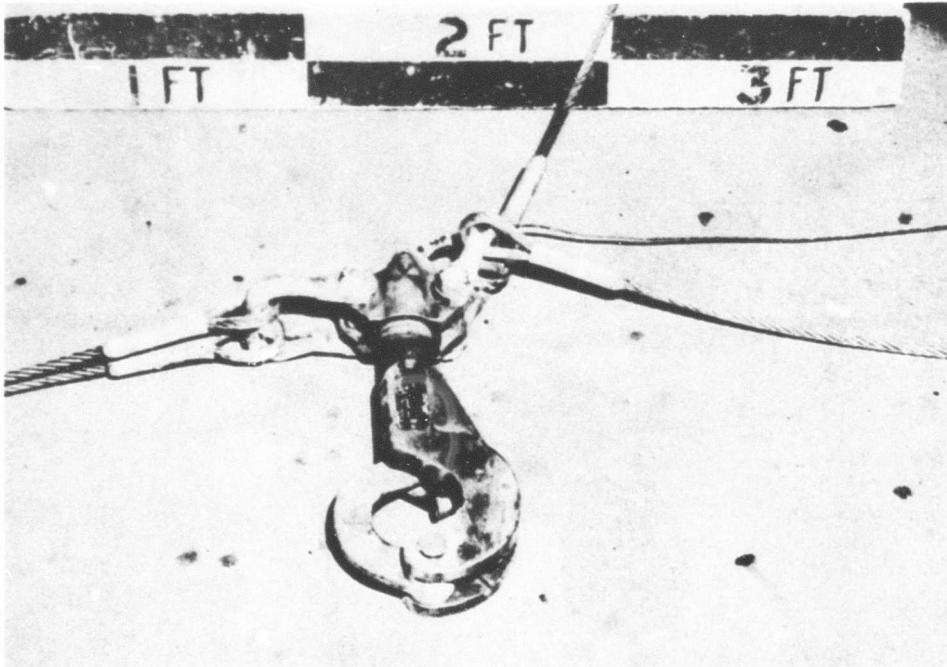


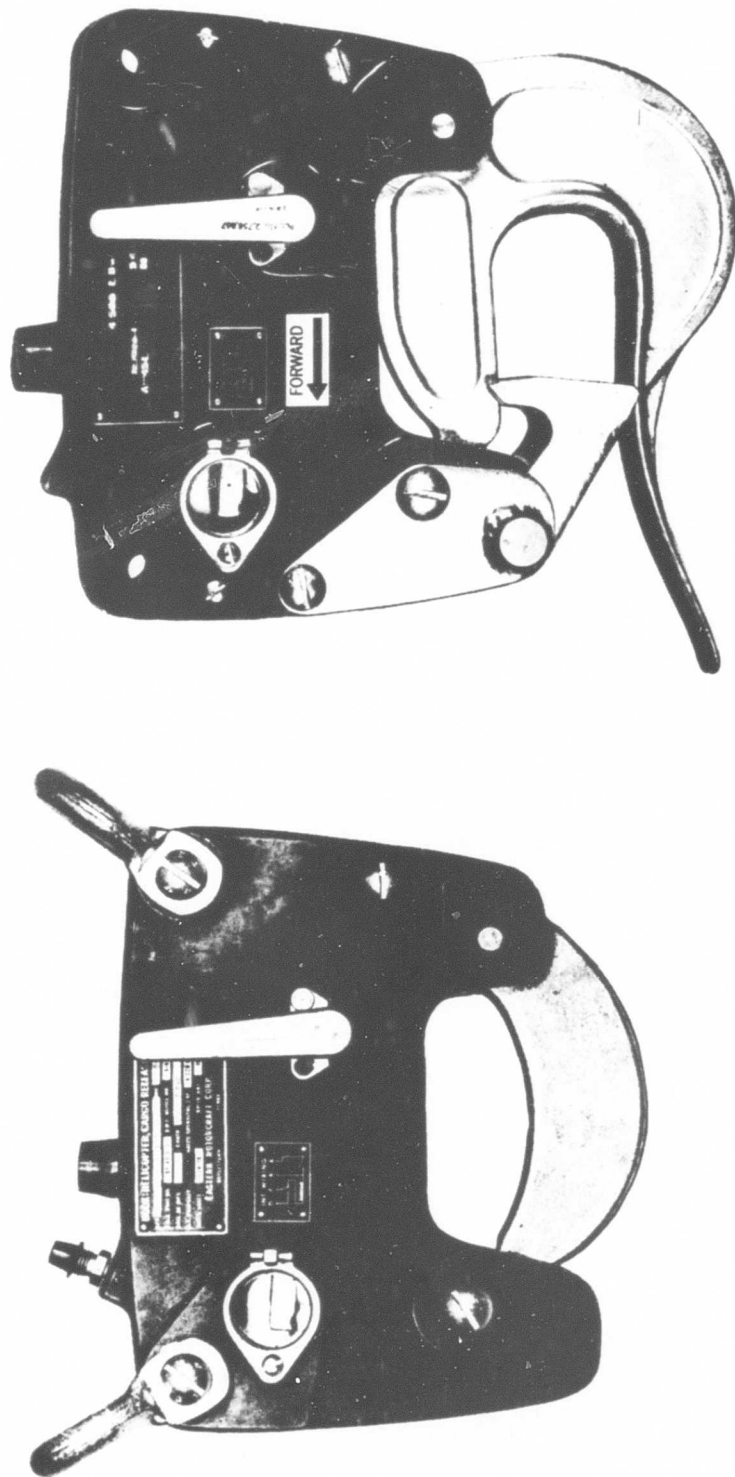
Figure 11. Early Cargo Hook

Hoist systems have been built with electrical conductors coaxial with the load cable. An example of this is the CH-54A single-point hoist system. However, assurance of adequate reliability for present and future hoist systems is dependent on the development of a military specification. Such a specification would cover the manufacture, test, and use of electrical conductors contained within load-carrying cables.

The parallel-conductor approach also presents innate problems on single-point suspension systems. In this case, the cable and conductor may become twisted together, resulting in damage to the conductor, or the conductor could be caught in the winch. This approach requires the aircraft to be equipped with a conductor take-up spool, either with a constant-tension reel-in device or with a powered winch.

It is customary to provide a swivel between the hook and cable on single-point suspension systems. The swivel must be fitted with integral slip rings if the hook is electrically operated (see Figure 13). Further, it is extremely difficult to provide a manual hook release with the hoist-mounted cargo winch. The usual solution to this problem is to employ a cartridge-actuated cable cutter. Such a device is, customarily, operated by electrical means; it is therefore subject to electrical

HELICOPTER CARGO RELEASE HOOK



**CAPACITY 4500 LBS.
HORIZONTAL LOADING**

Figure 12. Typical Cargo Hooks

failure. A hazardous situation could result from interruption of the aircraft's electrical supply, because the load could not then be released. The provision of a separate battery to electrically actuate the cable cutter assembly would create the additional maintenance of routine battery checks. Manually operated cable cutters are available but, to date, have not been employed on airborne hoist systems. Further investigation into the emergency release of hoisted loads is recommended.

Weight of Cargo Hooks

When discussing the weight of cargo hooks, it is extremely important to recognize the difference between hooks to be used in fixed installations and hooks intended for hoist applications. Cargo hooks designed for fixed installation may reflect weight savings derived from good detail design practices. Such a hook is the 20,000-pound-capacity Eastern Rotorcraft Model 2A-200, which weighs 40 pounds. Lightweight hoist-mounted hooks cannot be designed because the hook weight serves both to straighten the cable and to pull it from the winch. This feature may be commonly seen in commercial crane applications, where it is normal practice to fit a "headache ball" between the hook and cable (see Figure 14). This important weight feature is reflected in the weight of 75 pounds for the 12,000-pound-capacity hook fitted to the CH-54A (Eastern Rotorcraft Model A-120M), as compared to the 40-pound weight of the 20,000-pound-capacity fixed hook described above. Unfortunately, the problem is compounded when larger hook capacities are considered. Cable bending stiffness increases approximately as the square power of strength; consequently, cable capacity increases of from 20,000 pounds to 40,000 pounds require an increase in hook weight of $2^2 \times 75 = 300$ pounds.

To obtain a weight trend for hoist-mounted hooks in the 15- to 25-ton-capacity range, a study was made of hooks with swivel features that are used in commercial cranes. The results show that for a 15-ton system using a 1-inch cable, the hook weight is 364 pounds; for a 25-ton system using a 1-1/2-inch cable, the hook weight is 416 pounds (Miller Swivel Products, Inc., Pomona, California). The hook weight figures, shown above for commercial cranes, may be higher than those of similar hooks used on aircraft-mounted systems using equivalent-diameter cables. Increased hoist weight could also occur if newly developed, extra-high-strength cables or cables with coaxial conductors are used. The above cable types are stiffer than similarly rated semiflexible cables and, consequently, require

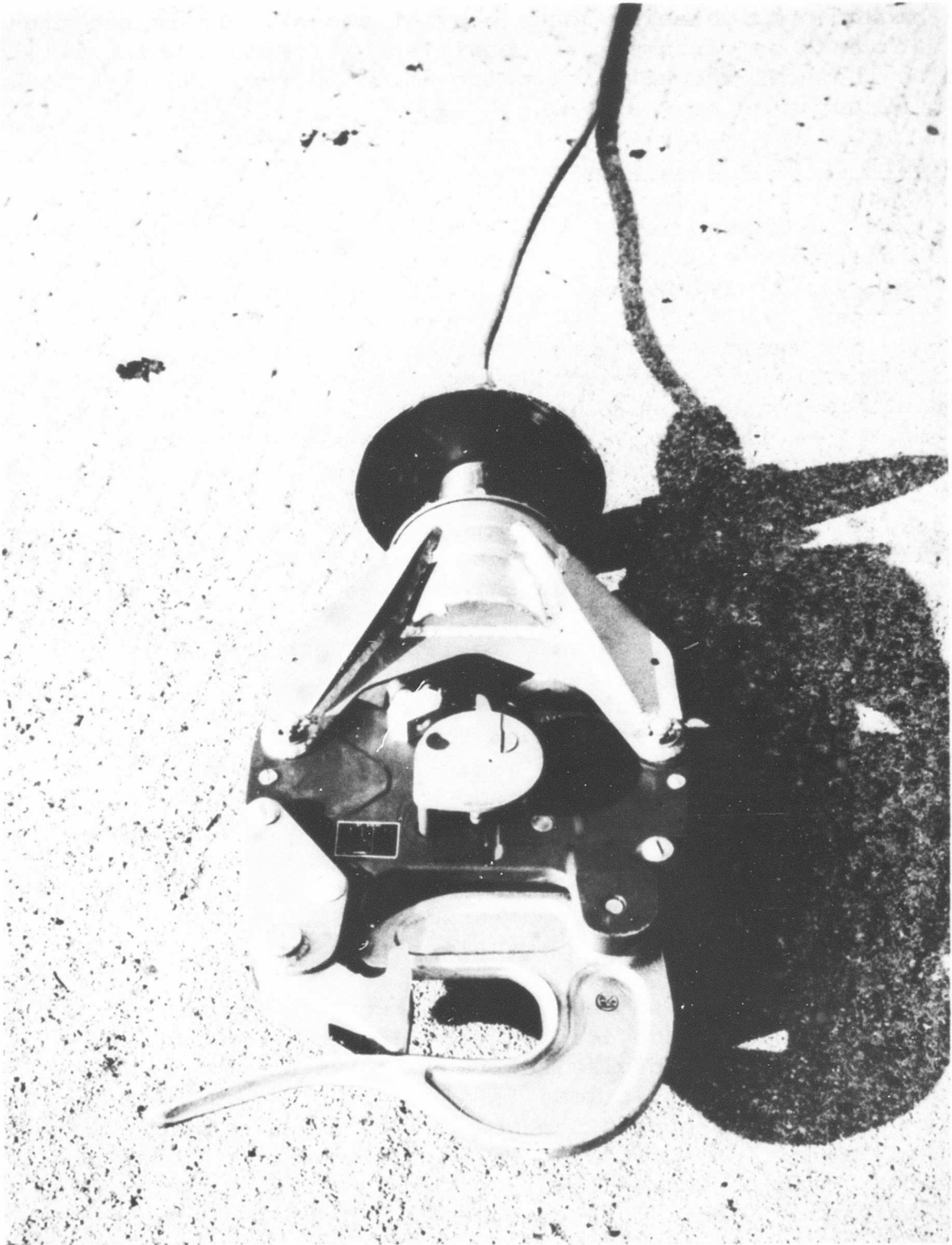


Figure 13. Electrically Released Cargo
Hook with Swivel and Slip Rings

a higher straightening load (heavier hooks). It is recommended that tests be performed to obtain specifications which will define the hook weight in relation to cable type and size for use in airborne hoist systems.

SINGLE-POINT SUSPENSION

Single-point suspension (see Figure 15) is the simplest and certainly the commonest way of carrying external loads. Single-point suspension systems can be divided into two different types: one incorporating some torsional restraint of the load, and the other having a swivel intentionally introduced into the system. Torsional restraint of the load is achieved by attaching the load sling to the cargo hook through a large ring. The ring serves to provide a base for the sling, as shown in Figure 16, and reacts the torque into the cargo hook in the same manner as the torque reaction of two interlocking rings under tension. If the ring was not used, the sling legs would twist on themselves, thus limiting the centering action to the load and possibly damaging the sling.

Occasionally it is necessary to lift a load on a very long sling, or a very long load on a short sling. In either case, when the torsional restoring moment afforded to the load is insufficient to guarantee that rotation will not occur, it is common practice to install a swivel into the system to minimize the risk of damage to the sling. It is also necessary to install a swivel on systems that use a single cable or pendant between the sling and helicopter, because a torsional load applied to the cable reduces the ultimate tensile load by changing the distribution of load between individual strands. A hook equipped with such a swivel is shown in Figure 13.

If it is necessary to carry aerodynamically unstable loads on long suspensions, the load must be either aerodynamically stabilized or torsionally restrained. An example of an aerodynamically stabilized load is given in Figure 17, which shows a CH-47A transporting a damaged CH-47A fuselage, with the load stabilized by use of a drag parachute. Stabilization of the load by drag parachute takes time and increases the total drag of the load. It is not, therefore, a suitable technique for use in the transportation of tactical loads, where aircraft productivity is important. Loads may be stabilized with only a small drag penalty by the addition of a vertical stabilizer surface, but this technique is unwieldy due to the size and difficulty of attaching a surface of sufficient size.



Figure 14. Hook with Headache Ball

Miller Swivel Products Company

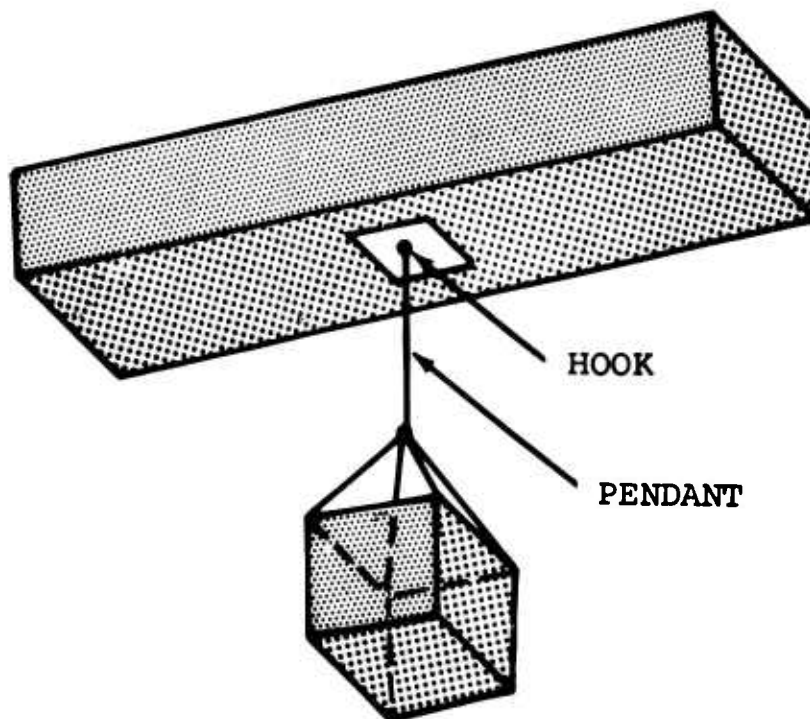


Figure 15. Single-Point Suspension

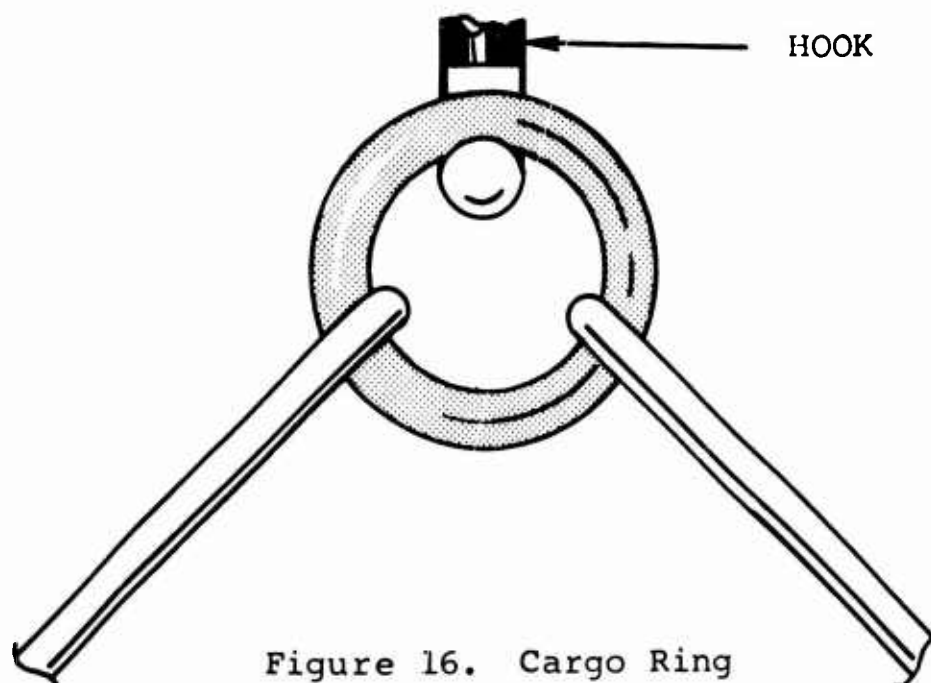


Figure 16. Cargo Ring

A technique being developed to stabilize loads for the vertical replenishment of ships by a UH-46A helicopter is shown in Figure 18. In this application, the use of long suspension is necessary to allow the helicopter rotors to clear the ship's rigging. The pendant consists of a torque tube with a cargo hook attached to the lower extremity. The load sling is attached to the lower cargo hook, and the system behaves torsionally as though the sling were attached to the fuselage hook.

In cases where long suspension is used continuously as part of the system, such as in the UH-46A mission described above, it is advisable to attach a pilot-controlled cargo hook at the lower end of the pendant. However, an emergency release may still be accomplished at the fuselage-mounted hook. Refer to the Cargo Hooks on Hoist Systems discussion on page 10.

A major factor in determining sling and suspension length is the phenomenon known as vertical bounce. Vertical bounce is a vertical vibratory motion of the fuselage and load at approximately 3 to 4 cycles per second, which may increase to such intensity as to cause the pilot to jettison the external load. Vertical bounce is not confined solely to aircraft carrying



Figure 17. Stabilization of Load by Means of Drag Chute

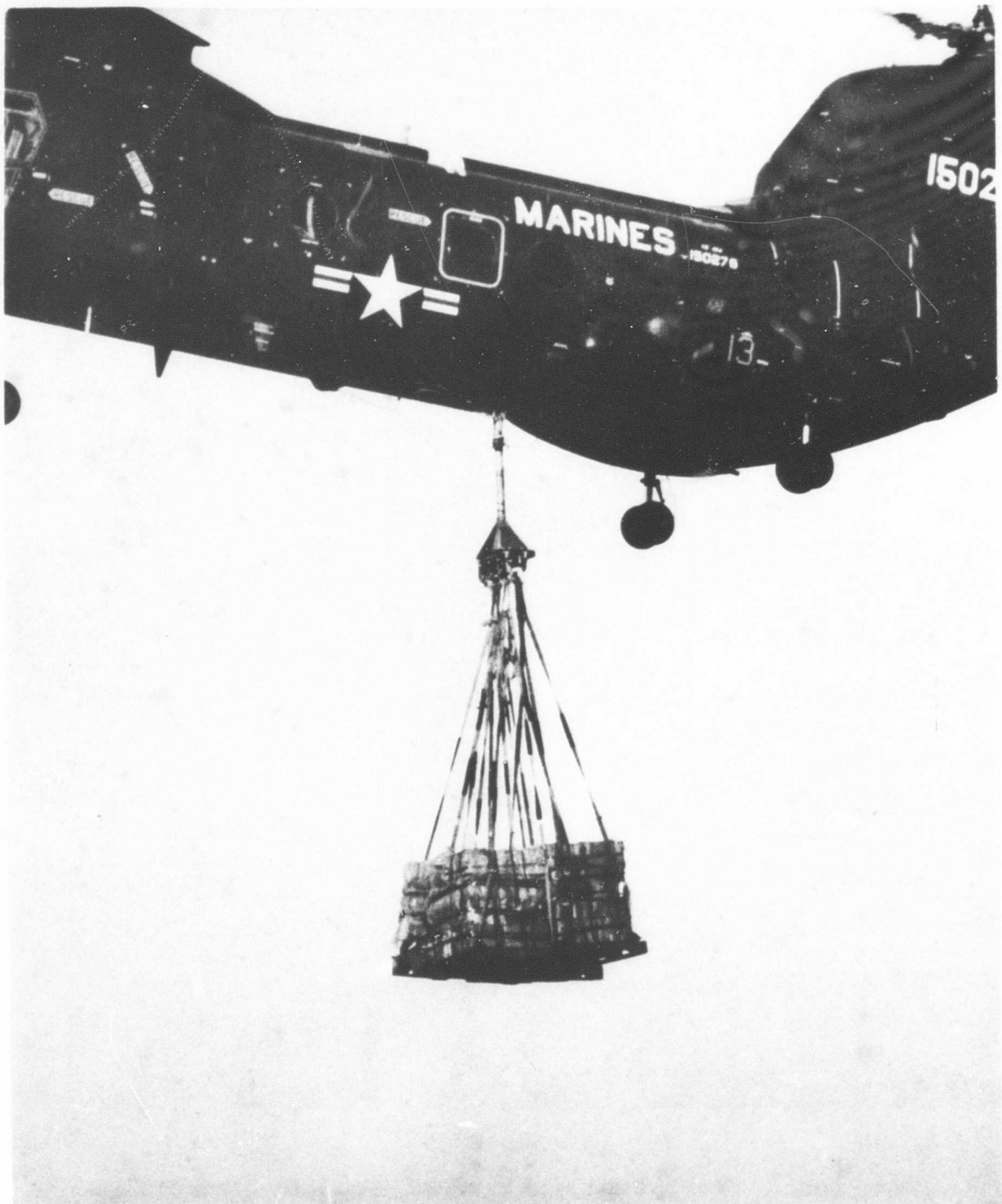


Figure 18. Torque-Tube Pendant

external loads, but it has proved to be a particular problem with external loads. The problem is aggravated by using a sling with a stiffness such that the load natural frequency in the vertical direction corresponds to the aircraft vertical bounce frequency. In the past, the problem has been minimized by selecting sling materials and lengths that cause the load bounce frequency to mismatch with the fuselage bounce frequency. Army experience with the CH-47A has indicated that, when using steel cable, suspension bounce becomes a problem over a wide range of lengths. This finding resulted in the recommendation that only nylon slings be used.

Another approach to the solution of the vertical bounce problem was taken on the CH-54A single-point hoist system. Since it was necessary to operate with variable-length suspension, it was not possible to guarantee that the suspension frequency would not match the bounce frequency. The solution was to fit a soft spring in series with the hoist; this maintained a low spring rate over the entire hoist travel. This system, known as a load isolation, has minimized the problem. Vertical bounce has not been encountered by the Army CH-54A pilots; it is important to note, however, that these pilots are all very experienced and they feel that the system may be unacceptable to an inexperienced pilot. Vertical bounce and load isolators are discussed in detail in the EFFECTS OF EXTERNAL LOADS ON HELICOPTER HANDLING, STABILITY, AND VIBRATION section which begins on page 123.

MULTI-POINT SUSPENSION

The advantage of a multi-point suspension is in the stability that it affords to the load. This type of suspension was introduced on the CH-54A crane-type helicopter shown in Figure 19. The original system on the CH-54A has four hard points to which a load leveling and lifting system is fitted. The system assembly consists of four servo cylinders, mounted in pairs to stationary fittings on each side of the aircraft. In this design, the lower ends of the servo cylinders are attached to a hinged beam assembly to which cargo lashing reels are mounted. Actuation of the servo cylinders raises or lowers the beam assemblies and the attached cargo lashing reels, thus raising or lowering any attached load. Each cargo lashing reel has a mechanical lock. The four-point system was designed to be compatible with a removable pod, the four points being available for suspending cargo when the pod was not fitted (see Figure 20).



Verti-Flyte Magazine

Figure 19. CH-54A Four-Point Suspension System

In practice, it is difficult to realize the benefits of multi-point suspension with the CH-54A four-point system. The four-point suspension system is structurally redundant because of the near impossibility of achieving equal loading in the legs. Unequal loading results in one leg being loaded substantially less than the other three legs or, worse, one leg being slack. The CH-54A system has the capability of "beeping" small extensions of the legs individually by means of the servo cylinders, but precise control cannot be maintained. Furthermore, a suspension that has been statically adjusted is not necessarily in balance in flight. The result of uneven loading is manifested as a coupling of the load motion in flight. That is to say, when the load moves aft due to aerodynamic drag forces, it may also move laterally and yaw. Such a load is difficult to control, since the pilot must make simultaneous corrections at different rates in all axes. Unequal loading may be remedied by rendering the system statically determinate; two schemes which would achieve this are shown in Figure 21. The schemes basically couple two adjacent legs together, thus guaranteeing equal loading.

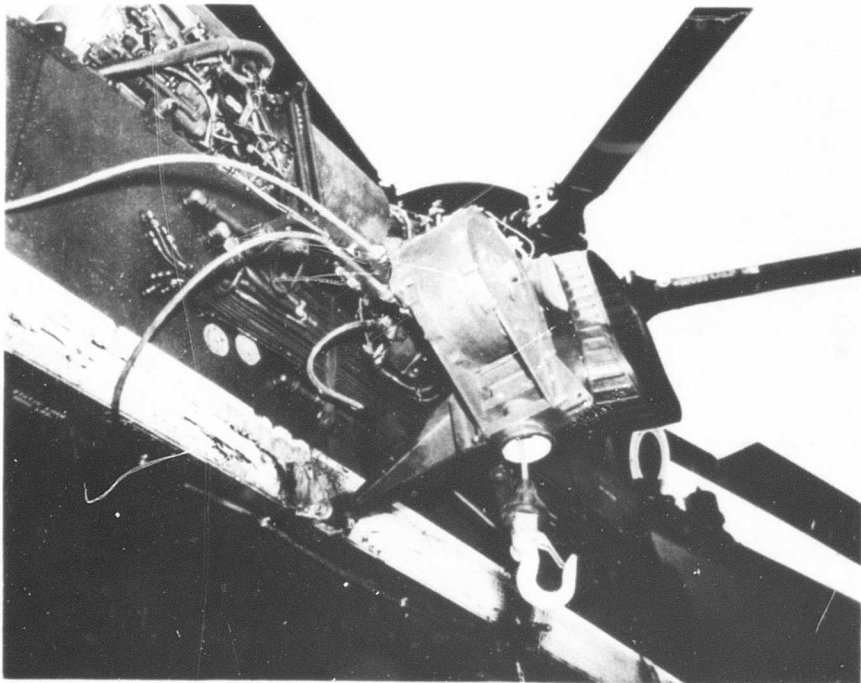


Figure 20. CH-54A Four-Point Suspension Cargo Lashing Reels and Leveling System

It is necessary to examine the requirements of load aerodynamic stability in order to determine the necessary features of a suspension system for stable high-speed flight. The discussion under STABILITY OF SLUNG LOADS, page 32, indicates that the primary restraining modes required from a suspension system are yaw and pitch.

The single-point suspension, discussed earlier in this section, offers only limited yaw and pitch restraint. Four-point suspension gives greater yaw and pitch restraint, together with increased roll restraint. Three-point suspension gives comparable yaw restraint without structural redundancy. Two-point suspension, oriented in a fore and aft fashion as shown in Figure 22, provides the desired pitch and yaw restraint and is structurally statistically determinate.

Multi-point suspensions offer advantages in load stability but incur problems in load release. Each leg of a multi-point suspension is equipped with a cargo hook. During release of the load, should any one hook fail to open and the pilot attempt to take off, the aircraft could be lost. Figure 23 illustrates the upsetting moment that would be created in such an eventuality. It might be argued that the likelihood of this happening is extremely rare. However, if a hook should become hung up, the pilot would probably not notice it until he had pulled away from the load. At that time he would sense the upsetting moment, but normal correcting procedures might well compound the problem; such an experience, which occurred with the original cargo sling, is described earlier in this section.

Experience with current cargo hooks has shown that these are not 100-percent reliable in releasing the load on command; they are, hence, fitted with secondary release mechanisms. A warning system could be devised to indicate when one hook is not released, but if the aircraft is hovering while releasing the load, a gust could raise the aircraft sufficiently to cause the suspension line to pick up the load with the consequence described above. Therefore, without a technique for the positive coupling of hook release mechanisms, multi-point suspensions constitute a safety hazard. A two-point suspension with a connecting beam, as shown in Figure 24, shows promise for a practical solution to this problem.

It has been said that the only difference between internal and external loads is that it is possible to jettison external

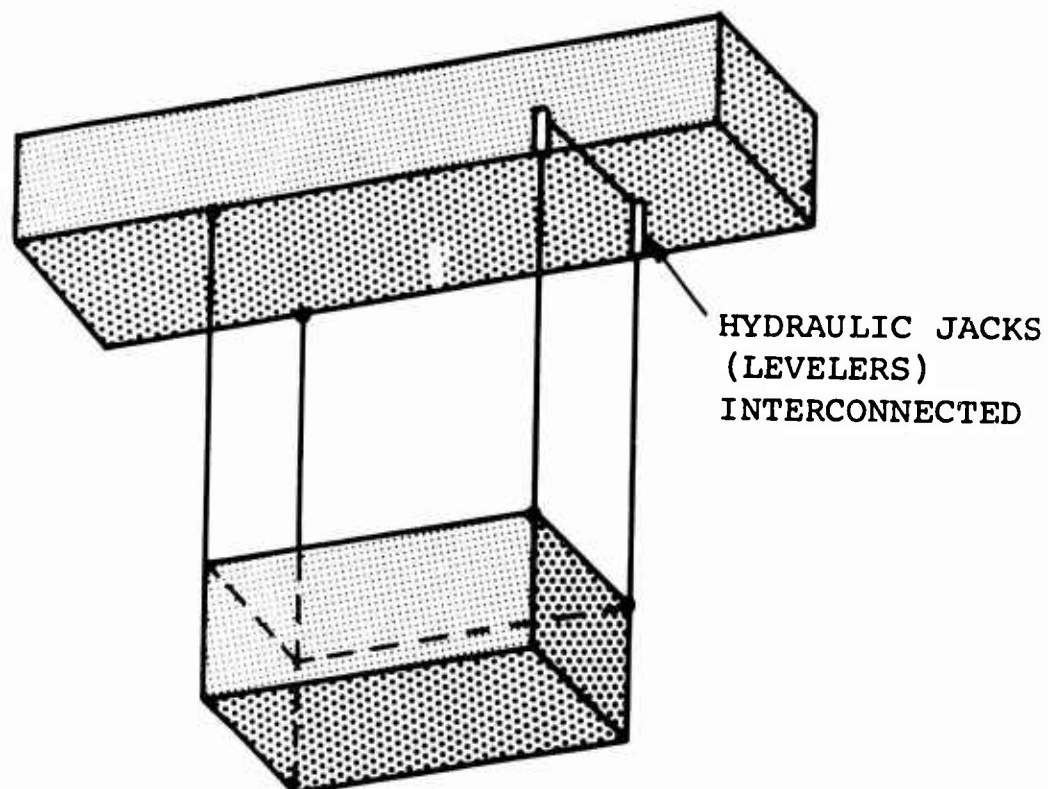
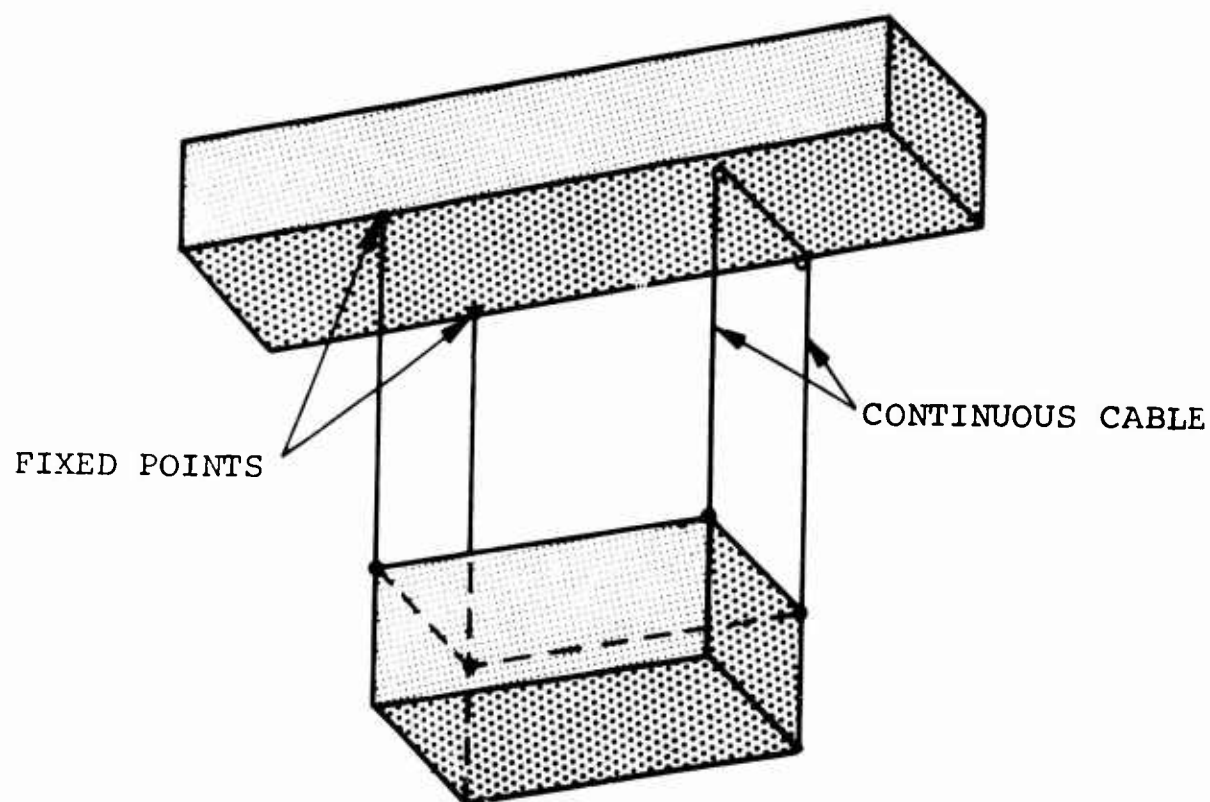


Figure 21. Techniques To Eliminate Redundancy in Four-Point Suspension

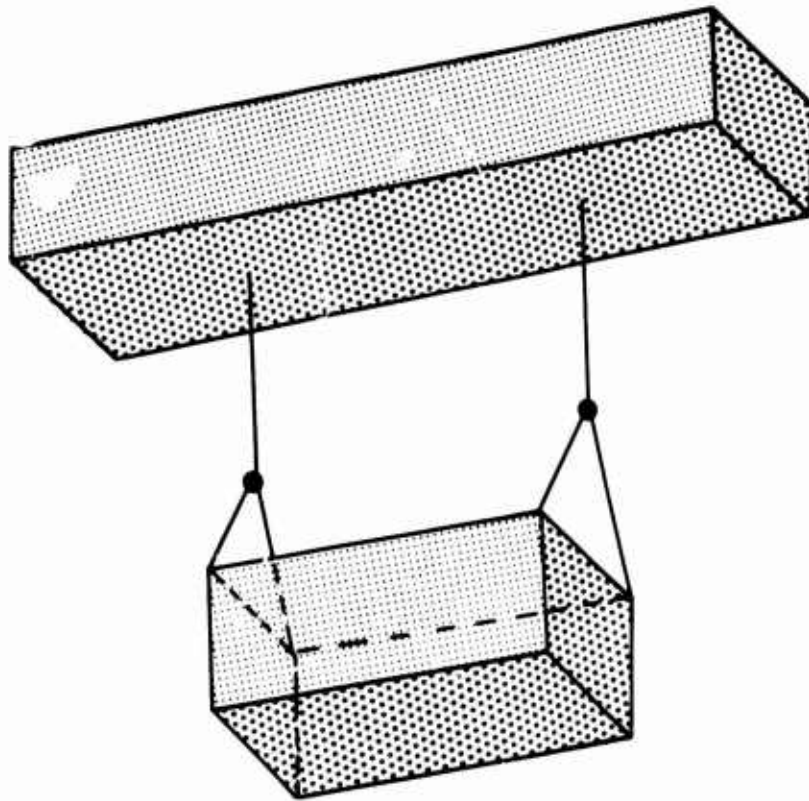


Figure 22. Simple Two-Point Suspension

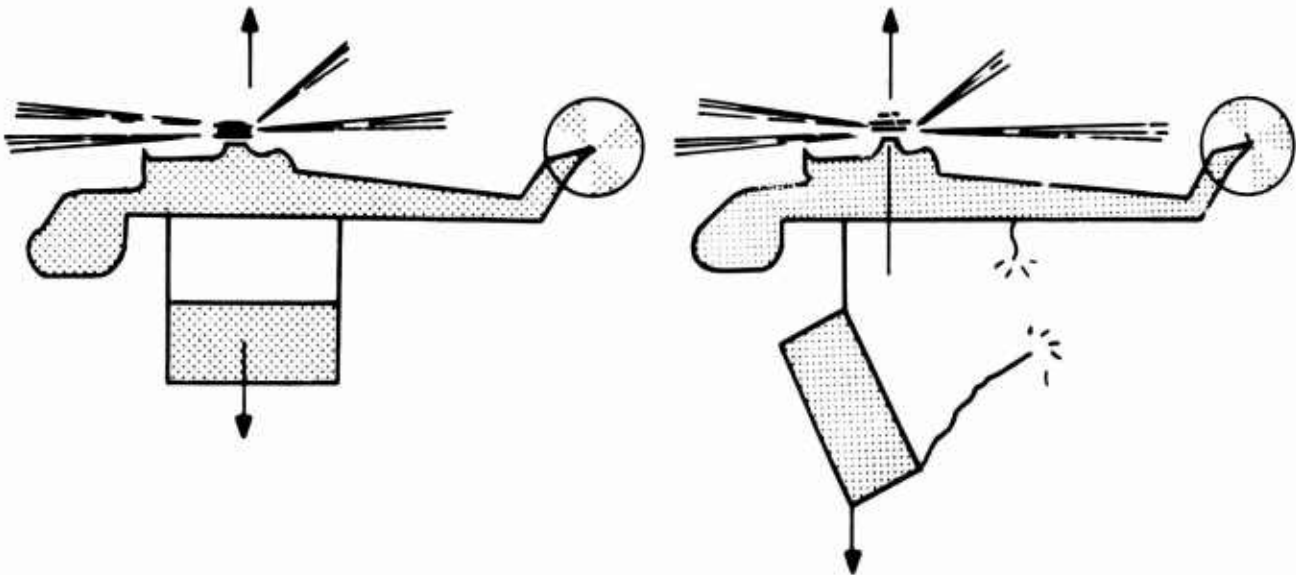


Figure 23. Effect of Partial Failure on Multi-Point Suspension

loads. It could be further argued that emergency release is not necessary, but experience has shown many times that dangerous conditions can result from load instabilities. Therefore, an emergency release capability must be fitted to any load suspension system that does not rigidly attach the load to the aircraft (such as a pod or platform).

As in the case of the pilot-controlled electrical load release, a two-point suspension with a connecting beam appears to offer the simplest means of positively coupling emergency release mechanisms.

The requirements for ground personnel to attach a load depend on the method of load acquisition. If the pickup is made with the helicopter on the ground, one man may connect all the hooks. However, if a hovering pickup is made, one man is required to ensure attachment of each hook, in order to prevent the pilot from inadvertently picking up a partially attached load, which could result in loss of the aircraft. In general, the availability of a multi-point suspension will not lessen the need for securing the load, since the majority of loads are not equipped with compatible pickup points. It is not usually possible to provide such pickup points, because of the diverse shapes of the loads.

Lateral swing of multi-point suspended loads creates the same aircraft rolling moment experienced with single-point suspension. Consequently, unless it is possible to attach the suspension at a waterline passing through the cg of the aircraft (as in the CH-54A), a curved beam (as used in the CH-47A), or equivalent, should be fitted to the aircraft (see Figure 8). Curved beam mechanisms are not feasible for four-point suspensions; such systems are not, therefore, suitable for mounting on the bottom of a transport helicopter. Two-point suspensions may be fitted to curved beams in exactly the same manner as single-point suspension systems (see Figure 25).

A helicopter equipped with a two-point suspension or hoist system is able to operate in a single-point mode by connecting both legs as shown in Figure 26. The angularity of the legs increases leg loading and is contained within the known factor for uneven loading. The aforementioned technique actually provides a single-point system which is an improvement over a system using a single pendant, because the torsional restoring moment afforded the load is increased, and the cable diameters may be reduced.

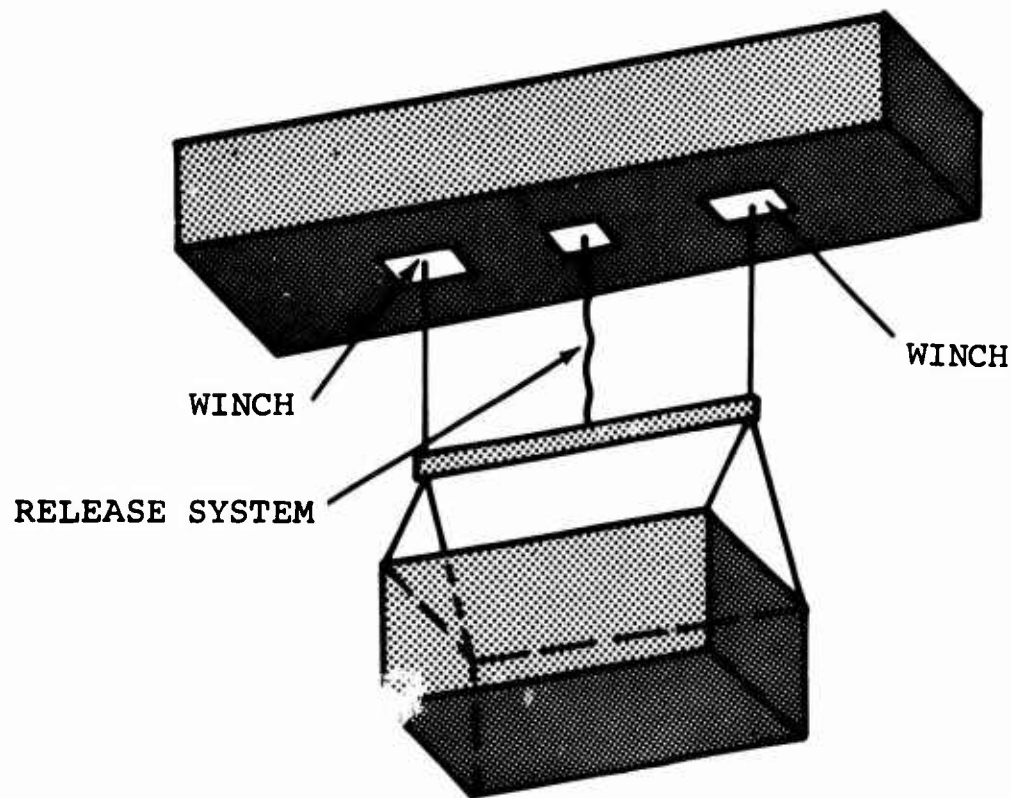


Figure 24. Two-Point Suspension with Connecting Beam
Sling Load Isolator

One of the methods which is available for dealing with the problem of sling load vertical bounce is the concept called the load isolator. Schematically, the system consists of a soft spring placed in series with the external load sling, between the helicopter and the external load sling. Natural frequency of this spring is designed to be well below the once-per-rotor-revolution bounce excitation frequency of the helicopter. This dynamically soft link in the external load system prevents the external load/sling combination natural frequency from ever coinciding with the rotor excitation frequency.

This can be seen by considering the equation for the resultant spring rate of a series spring combination

where

K_R = Resultant spring rate (lb/in.),

K_1 = Load isolator spring rate,

K_2 = Sling spring rate.

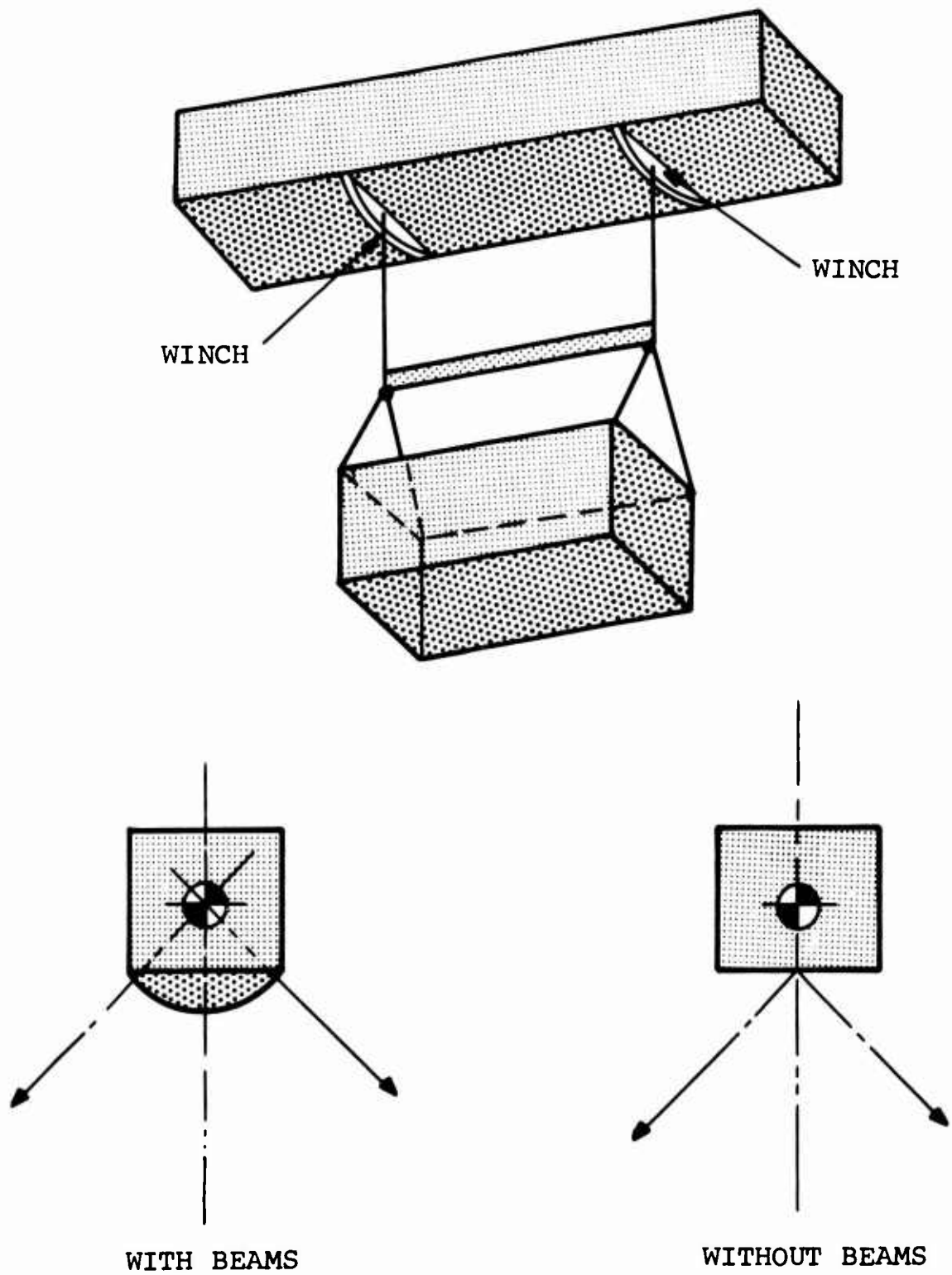


Figure 25. Two-Point Suspension with Curved Lateral Beams

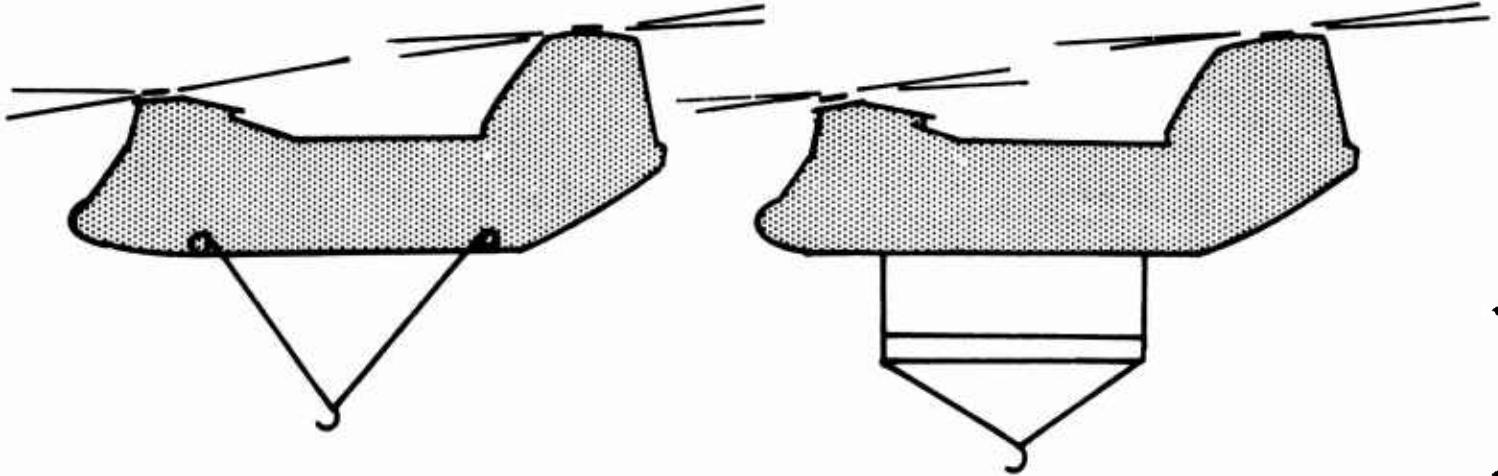


Figure 26. Single-Point Lift from Two-Point System

When a load isolator is used, K_1 is essentially a constant. The spring rate of the sling (K_2) is a variable and can be any value. The resultant spring rate (K_R) then can have a range of

$$0 < K_R < K_1 . .$$

Using only the linear theory, the relationship between spring rate and natural frequency is

$$\omega = \sqrt{\frac{K_R}{m}} \quad (1)$$

where

ω = Natural frequency (rad/sec),

K_R = Resultant spring rate (lb/in.) ,

m = External load mass $\left(\frac{\text{lb-sec}^2}{\text{in.}} \right)$.

Natural frequency is thus proportional to spring rate and will vary in a similar manner

$$0 < \omega_N < \omega_I$$

where

ω_N = Resultant natural frequency (rad/sec),

ω_I = Load isolator natural frequency (rad/sec).

This shows that the resultant natural frequency of any external load and sling in series with a load isolator will always be less than, or at most equal to, the natural frequency of the load isolator alone.

The above analysis indicates the way in which a load isolator operates. However, there are many considerations in defining an operationally acceptable system, such as:

1. Configuration - The load isolator must be capable of supporting the full static and dynamic weight of the external load, in addition to possessing the required low natural frequency. Obtaining the proper natural frequency is a challenge, since most helicopters require a load isolator natural frequency of between two and four cycles per second over a wide temperature range and with adequate damping. At present, both pure liquid springs and air springs are being investigated as means of providing the required characteristics.
2. Adaptation - Of necessity, the load isolator becomes an integral part of the helicopter. This is dictated by the requirement that it be in series with the external load and, yet, not interfere with the hook release system.
3. Weight Penalty - Present load isolator designs with capacities up to 25,000 pounds weigh between 50 and 150 pounds. The addition of a mass of this magnitude to the weight of a helicopter must be completely justified, particularly if it is carried during missions where external cargo is not transported.

Load isolators have the potential of becoming the complete solution to sling load vertical bounce. It is premature at present to predict the success which will attend efforts to convert theory to reasonable hardware, to meet reliability requirements, and to overcome resistance to the addition of any more heavy accessories to helicopters.

STABILITY OF SLUNG LOADS

The behavior of slung loads in forward flight is dependent on the aerodynamic characteristics and the suspension and sling geometry of the loads. Experience indicates that in most cases the maximum speed of the helicopter is limited by the effect that load oscillations have on the handling qualities. Actual instability of the load does not limit the speed of the helicopter as much as do load oscillations, when they reach an amplitude which the pilot considers unsafe. A second form of speed limitation is the aerodynamic drag of the load causing an aircraft to pitch down; this causes excessive "back stick" trim. Pitch-down condition is affected by the vertical location of the tow point with respect to aircraft cg, and the aircraft's control power in pitch. The tandem-rotor helicopter has inherently more pitch control power than either articulated or hingeless single-rotor helicopters. Pitch-down is overcome in the CH-54A by designing the tow point close to the cg. Helicopter speed limitations are subject to pilot judgment; therefore, a wide variation in causes exists. However, a study of unstable aircraft modes and the speeds at which instability occurs provides a means of comparing different systems.

Aerodynamics of External Loads

External loads may be classed aerodynamically in three groups; namely, high-density axisymmetric, high/medium-density elongated-body, and low-density high-drag.

High-density axisymmetric loads consist, typically, of netted loads of ammunition or a cluster of fuel bags. High-density loads are, generally, aerodynamically stable and may be flown at high speeds, using single-point suspension. The CH-47A has demonstrated flight in excess of the flight envelope with such loads (see Figure 27).

High/medium-density elongated-body loads consist, typically, of vehicles, missiles, etc. (see Figure 28). Loads of this type usually exhibit aerodynamic yaw instability; the loads do not naturally align the major axes with the line of flight. When flown on single-point suspension, where the aligning torque is limited, such loads usually rotate to present the side area of the load to the line of flight, resulting in a high-drag situation. Oscillation of the load in forward flight also occurs. When carried by multi-point suspension, where the

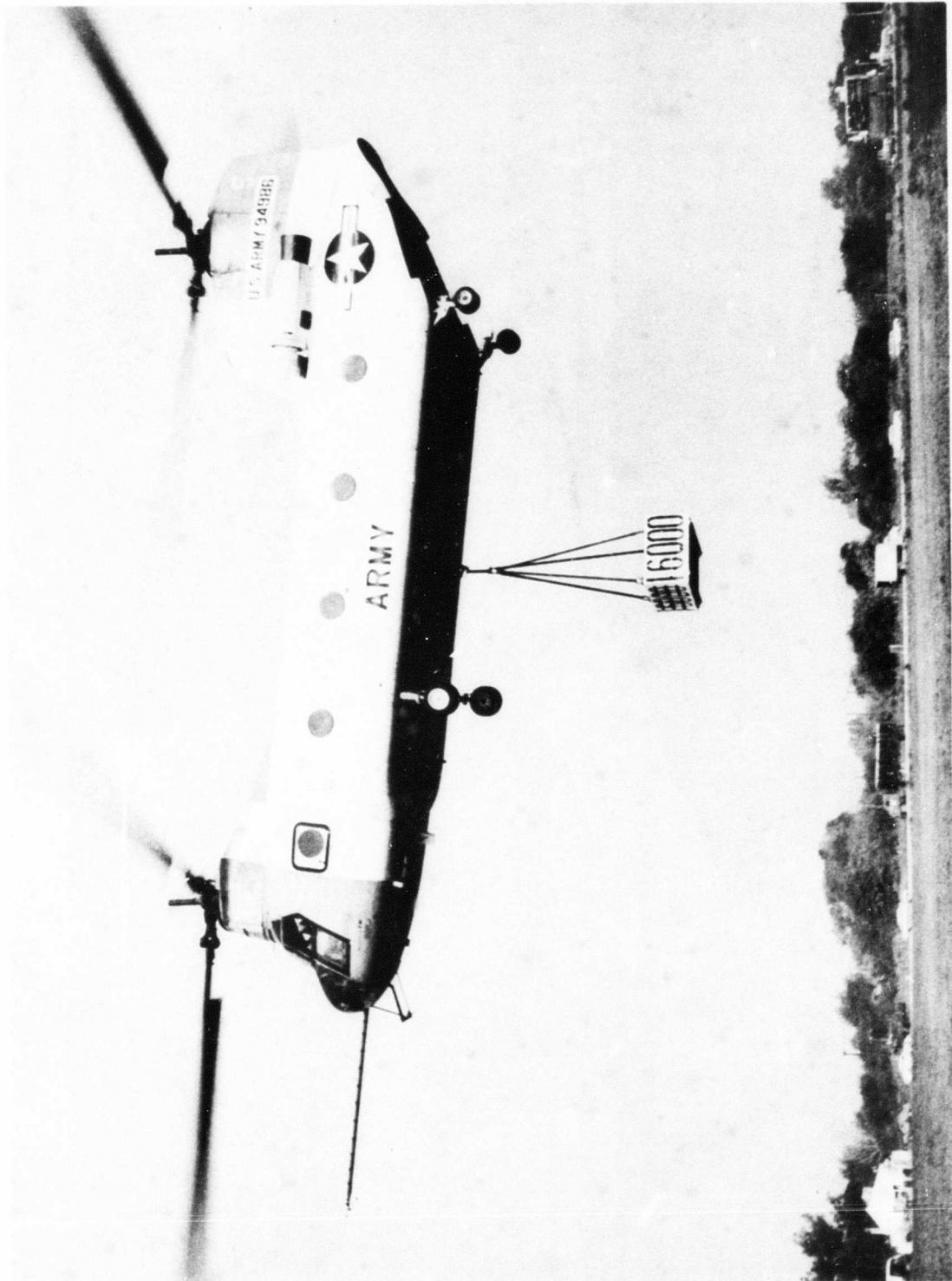


Figure 27. CH-47A Transporting High-Density Load

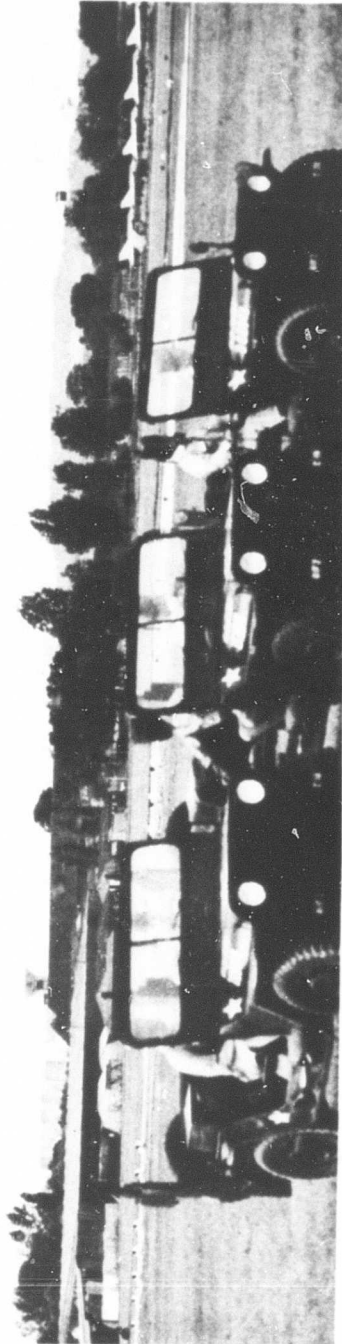
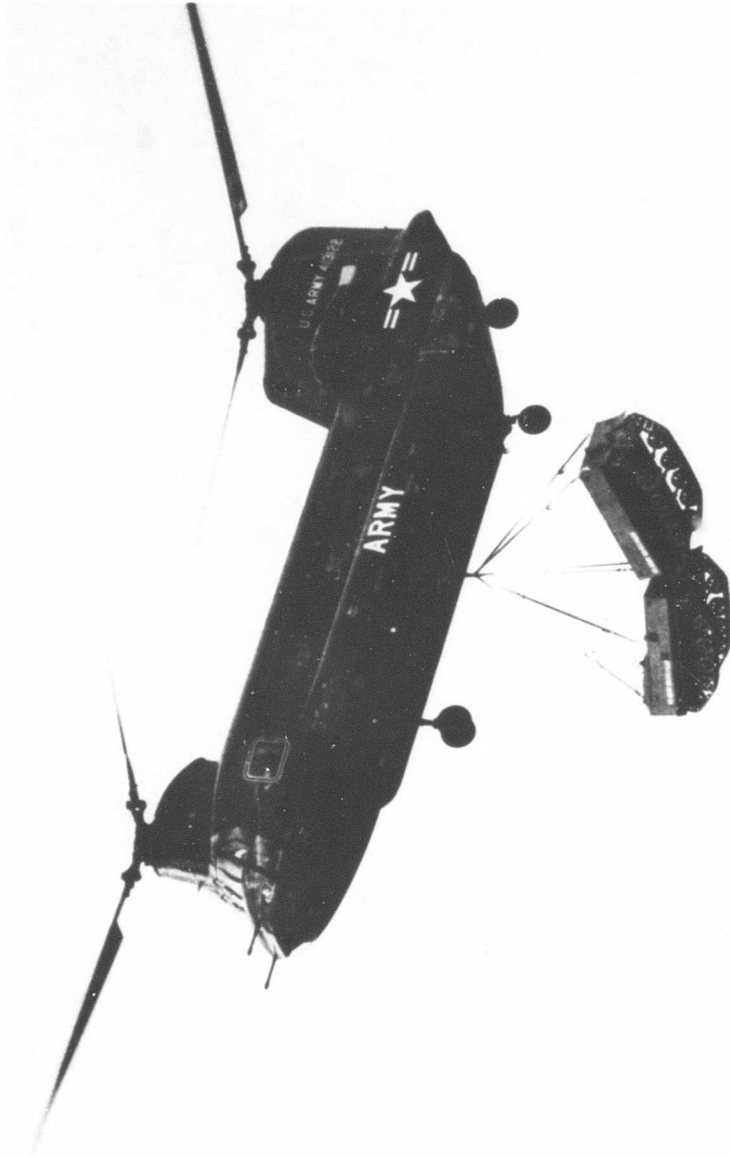


Figure 28. CH-47A Transporting Tracked Vehicle

aligning torque is high, high/medium-density loads may be flown at increased speeds. Speed limitations may then occur because of high-amplitude coupled motions, as described later in this section under Coupled Yaw/Lateral and Yaw/Longitudinal Motions (see page 40).

Low-density, high-drag loads are, typically, damaged aircraft, radar shacks, etc. (see Figure 1). Many loads of this type are aerodynamically unstable in yaw and pitch. Also, because of the high drag and large changes of drag with incidence of the load, the forward speed of the helicopter is very limited (typically, 40-50 knots for aircraft recovery). Aerodynamic stabilization of the load by drag chute, or other means, is advisable, particularly with single-point suspension. Because of load bulk, the loads are usually carried on long suspensions; this reduces the effectiveness of the multi-point suspension. Low-density loads which are not aerodynamically unstable may be flown at increased speeds. Then the helicopter is either power-limited or control-limited. Figure 29 shows the lunar excursion module (LEM) adapter being transported by a CH-47A. The LEM adapter weighs 4700 pounds, has a 260-inch base diameter, is 336 inches high, and is surmounted by a 240-inch tower. Extensive wind tunnel tests were performed prior to actually transporting the LEM adapter, which is fairly stable. It was flown as fast as 70 knots in test, but actual cruise speed during delivery to Cape Kennedy was 50 knots.

Yaw Divergence

The source of most stability limitations of external loads is the motion known as yaw. Since most loads exhibit varying degrees of aerodynamic yaw instability as described above, it is desirable to provide a stabilizing influence by way of suspension. With single-point suspension, it is common to connect the sling to the hook with a ring (see Figure 30). The result is that, for certain yaw motions about the central position, the ring rotates on the hook and at some position the ring climbs the hook and provides some yaw restraint. Further rotation of the load then causes the sling to wind up on the ring as shown in Figure 31. The resulting aligning torque is expressed as

$$T_{\psi} = \frac{aB}{H} \cdot \psi \sqrt{W^2 + D^2} \text{ (in.-lb)}, \quad (2)$$

where a is small with respect to B .

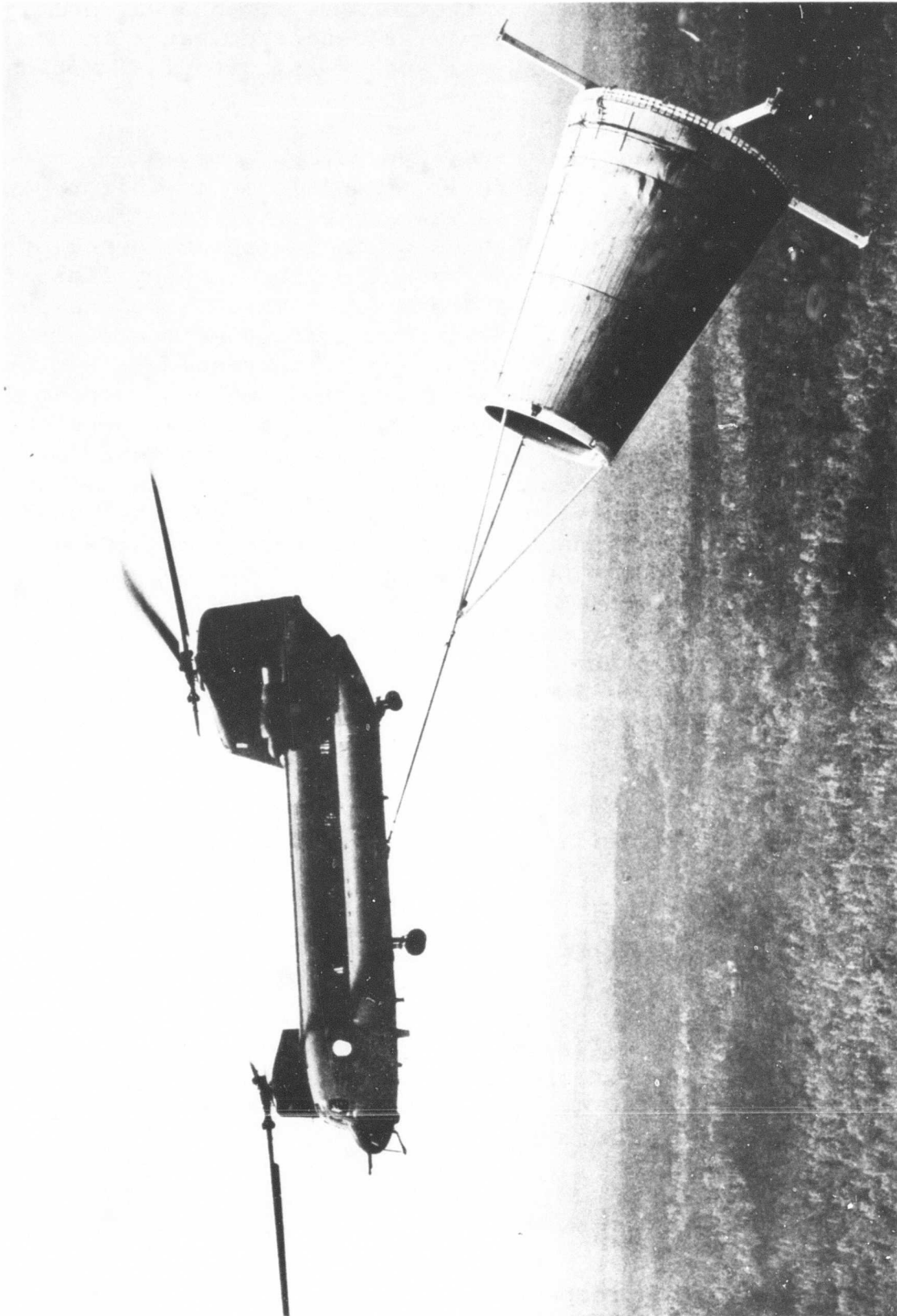


Figure 29. CH-47A Transporting LEM Adapter

The aligning stiffness is

$$\frac{dT_{\psi}}{d\psi} = \frac{aB}{H} \sqrt{W^2 + D^2} \quad (\text{in.-lb/rad}). \quad (3)$$

Pure yaw divergence occurs at the speed where the suspension righting torque equals the aerodynamic upsetting moment. This may be calculated from knowledge of the load aerodynamics. For the purposes of this study, an analysis will be made. The consideration for study of a typical load is an ellipsoid of circular cross section, with 20-foot length, 5-foot diameter, and 12-ton weight. Aerodynamic data for this body, found in Reference 11, are as follows:

For small angles, the yawing moment derivative

$$\frac{dC_m}{d\psi} = 2.0.$$

Then yawing moment derivative

$$\frac{dM}{d\psi} = q.S.\ell.\frac{dC_m}{d\psi} \quad (4)$$

where

$$q = 1/2\rho v^2,$$

$$S = \text{body frontal area,}$$

$$\ell = \text{body length,}$$

and at neutral yaw stability,

$$\frac{dT}{d\psi} - \frac{dM}{d\psi} = 0. \quad (5)$$

Example:

Evaluating the aligning stiffness of a single-point-suspension, as shown in Figure 31, with the following dimensions:

$$a = 0.33 \text{ ft,}$$

$$B = 10.00 \text{ ft,}$$

$$H = 20.00 \text{ ft,}$$

$$W = 24,000 \text{ pounds,}$$

$$\frac{dT_{\psi}}{d\psi} = \frac{1}{6} \sqrt{24000^2 + D^2} \quad (\text{ft-lb/rad}),$$

where D is the load aerodynamic drag, defined as

$$D = q.S.C_d.$$

This is negligible in this example; therefore

$$\frac{dT_{\psi}}{d\psi} = 4000 \quad (\text{ft-lb/rad}).$$

Substituting the above values into Equation 4 we get

$$\frac{dM}{d\psi} = .943v^2 \text{ (ft-lb/rad)}.$$

Alignment torques for two- and four-point suspensions, as shown in Figure 32, are as follows:

Four-Point:

$$\frac{dT\psi}{d\psi} = \frac{B^2 + C^2}{H} \sqrt{W^2 + D^2} \text{ (ft-lb/rad)}, \quad (6)$$

Two-Point:

$$\frac{dT\psi}{d\psi} = \frac{B^2}{H} \sqrt{W^2 + D^2} \text{ (ft-lb/rad)}, \quad (7)$$

For the numerical example described above, evaluate the yaw divergence speed, neglecting drag, for the following two- and four-point suspensions:

Two-Point: $H = 20 \text{ ft}$ $B = 10 \text{ ft}$

Four-Point: $H = 20 \text{ ft}$ $B = 10 \text{ ft}$ $C = 5 \text{ ft}$

Two-Point:

$$\frac{dT\psi}{d\psi} = 120,000 \text{ (ft-lb/rad)}$$

Four-Point:

$$\frac{dT\psi}{d\psi} = 150,000 \text{ (ft-lb/rad)}$$

A graph, in Figure 33, shows the load upsetting moment and the suspension righting moments. Below are indicated the speed limitations in this mode:

Single-Point: 69 feet per second

Two-Point: 356 feet per second

Four-Point: 398 feet per second

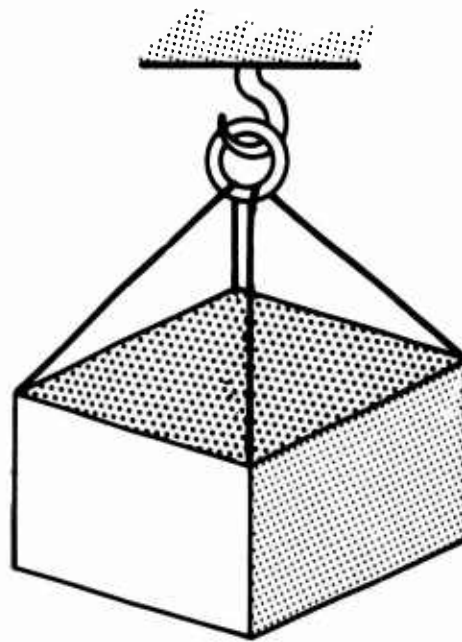


Figure 30. Sling Terminating in Ring

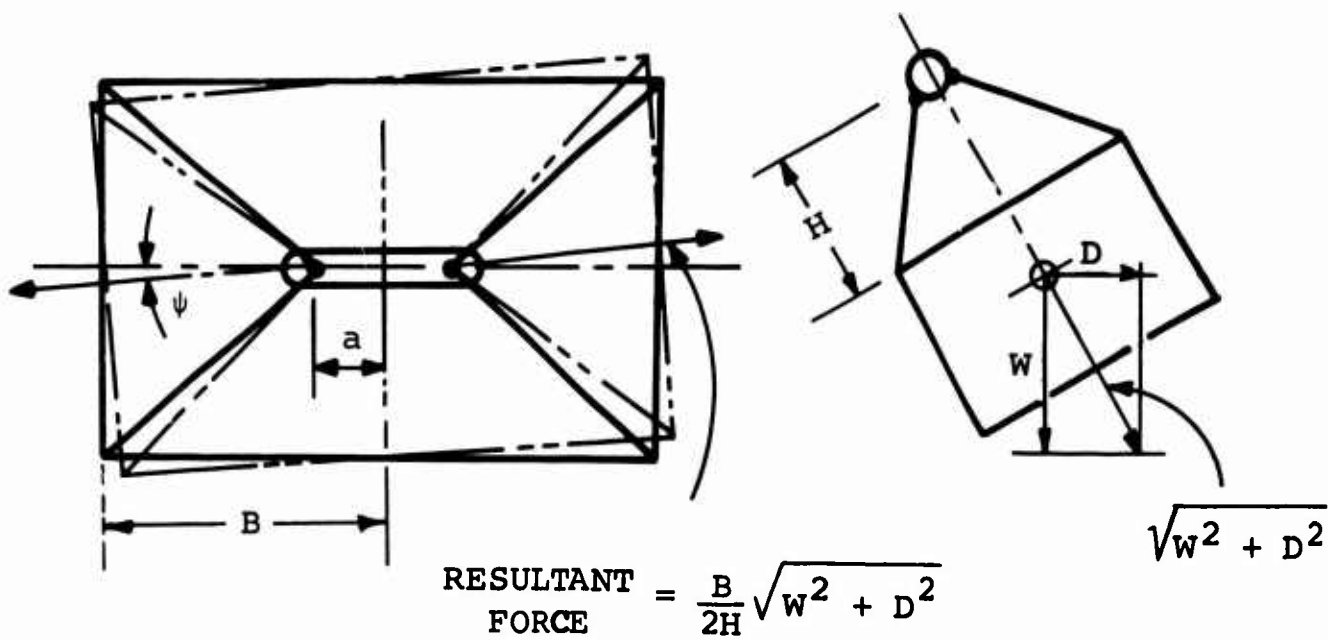


Figure 31. Aligning Torque on Single-Point Suspension

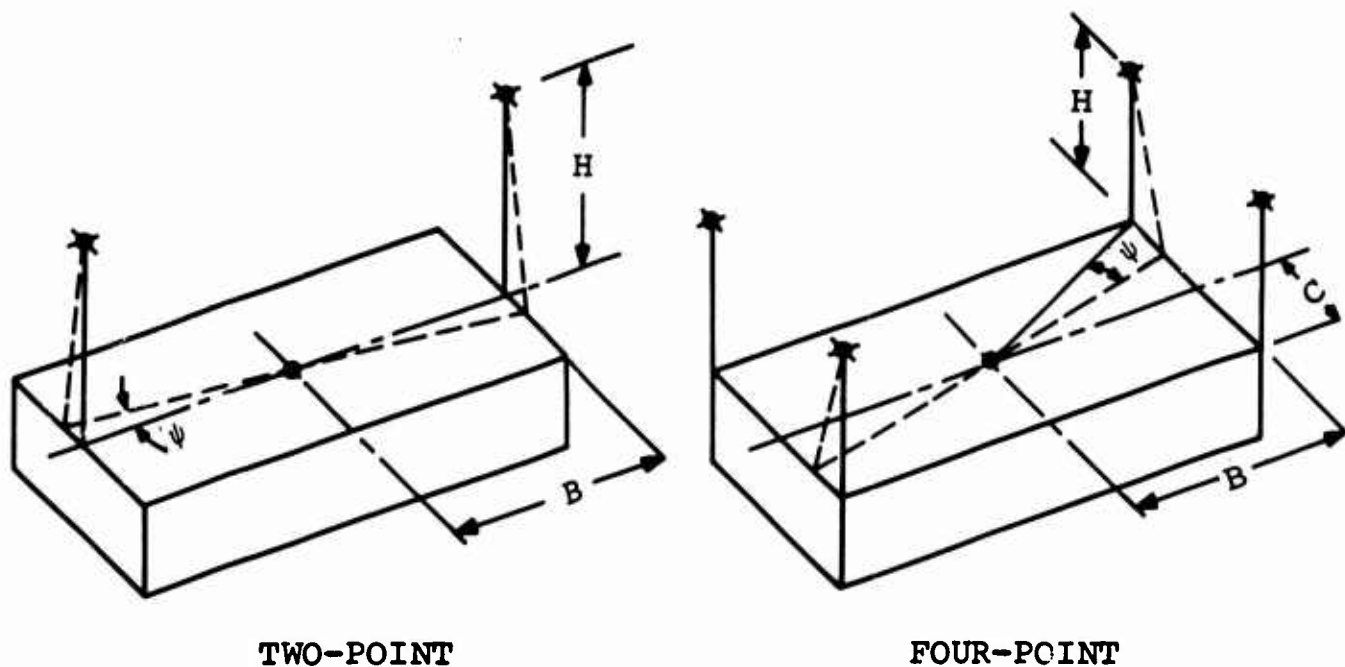


Figure 32. Aligning Torque on Multi-Point Suspension

Coupled Yaw/Lateral and Yaw/Longitudinal Motions

When a typical load yaws in forward flight, there is a corresponding change in aerodynamic drag and lateral force which causes the load to deviate in the forward direction. These coupled motions become of particular importance when the frequencies of oscillations coincide. Particularly for yaw/lateral oscillation, a coupled mode occurs when the yaw and lateral frequencies are equal. For yaw/longitudinal oscillations, the mode occurs when the longitudinal frequency is twice the yaw frequency.

The expression for the simple pendulum frequency of oscillation in longitudinal and lateral modes for single and parallel legs, in two- and four-point suspension, is

$$w_{\ell} = \sqrt{\frac{g}{H}} \sqrt{1 + \left(\frac{D}{W}\right)^2} \text{ (rad/sec)}, \quad (8)$$

which reduces where drag may be ignored ($D \rightarrow 0$) to

$$w_{\ell} = \sqrt{\frac{g}{H}} \text{ (rad/sec)}. \quad (9)$$

Frequency of yaw oscillations is a function of yaw inertia of the load and of the net righting moment equation (5):

$$\omega_{\psi} = \sqrt{\frac{\frac{dT_{\psi}}{d\psi} - \frac{dM}{d\psi}}{I_{\psi}}} \quad (\text{rad/sec}). \quad (10)$$

Figure 34 is a plot of yaw, longitudinal, and lateral frequency for the example previously discussed. Points of coalescence between yaw frequency and half longitudinal frequency, for the two- and four-point suspension, occur at 348 and 390 feet per second, respectively. This coupled mode is usually well damped and would not be expected to give serious problems, unless the aircraft is forced to cruise at the above-mentioned speeds. Points of coalescence between yaw and lateral frequency for the two-point and four-point suspensions occur at 328 and 371 feet per second, respectively. Coupled yaw/lateral oscillations can be troublesome, since the damping is low, resulting in the buildup of very high amplitudes, particularly if the frequency match occurs at high airspeeds.

Pitch/Longitudinal Motions

Pitch stability of the load is important only when considering single-point suspension or multi-point suspension with inclined legs. Pure pitch divergence is not usually a problem, due to the intimate coupling between pitch and longitudinal motions. Pitch/longitudinal motions become a severe problem when the load has a marked change of drag with incidence, such as in carrying a flat plate edgewise through the air. The forces acting on such a system are shown in Figure 35; the criterion for static pitch stability is

$$\frac{dC_m}{d\alpha} + h \cos (\gamma + \theta) \left\{ \frac{dC_d}{d\alpha} - \frac{W}{qS} \right\} - h \sin (\gamma + \theta) \frac{dC_{\ell}}{d\alpha} \geq 0 \quad (11)$$

where

$$\tan \theta = \frac{D}{L+W}$$

and

$$\sin \gamma = \frac{M}{h \sqrt{(L+W)^2 + D^2}} \quad .$$

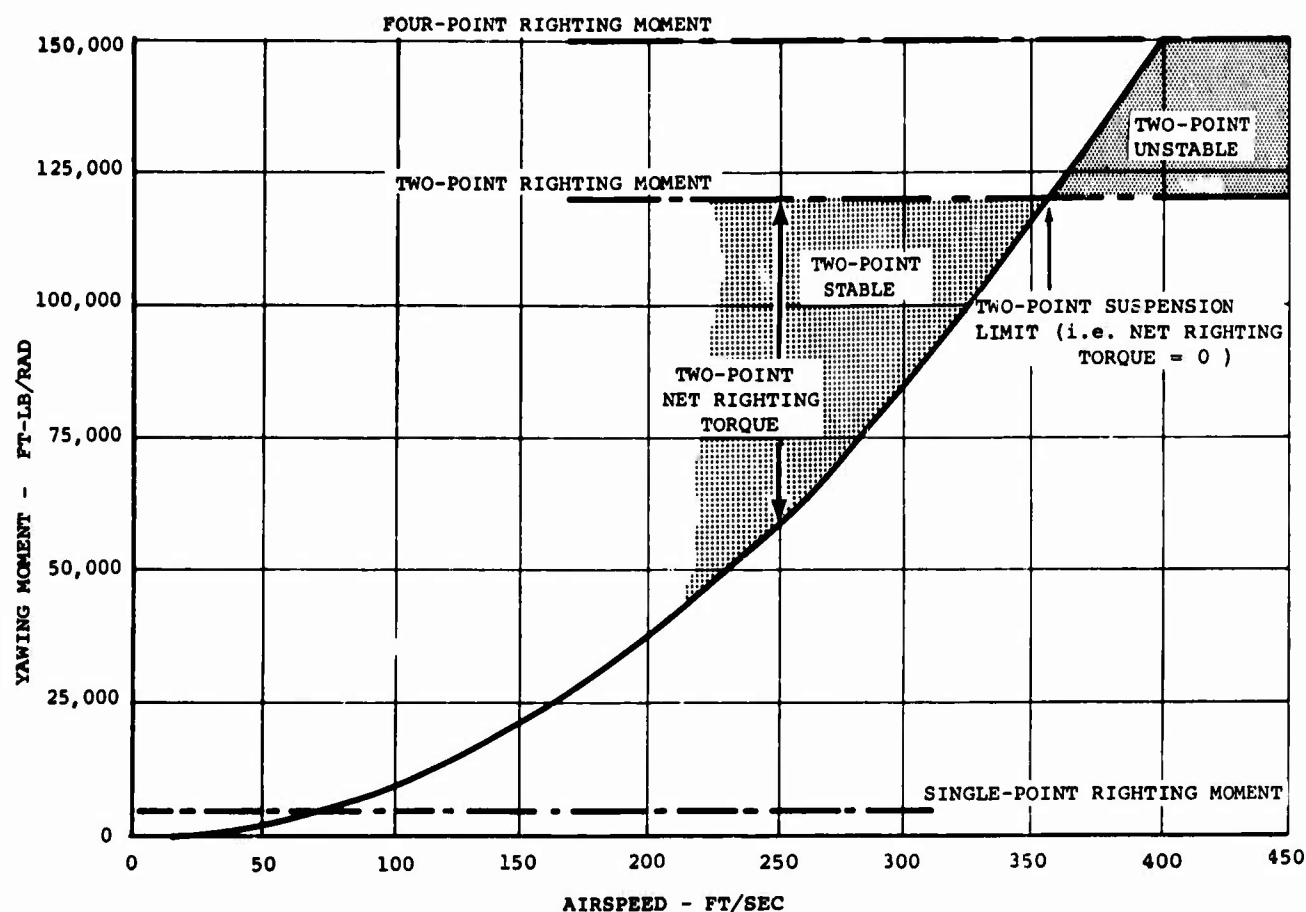


Figure 33. Pure Yaw Divergence

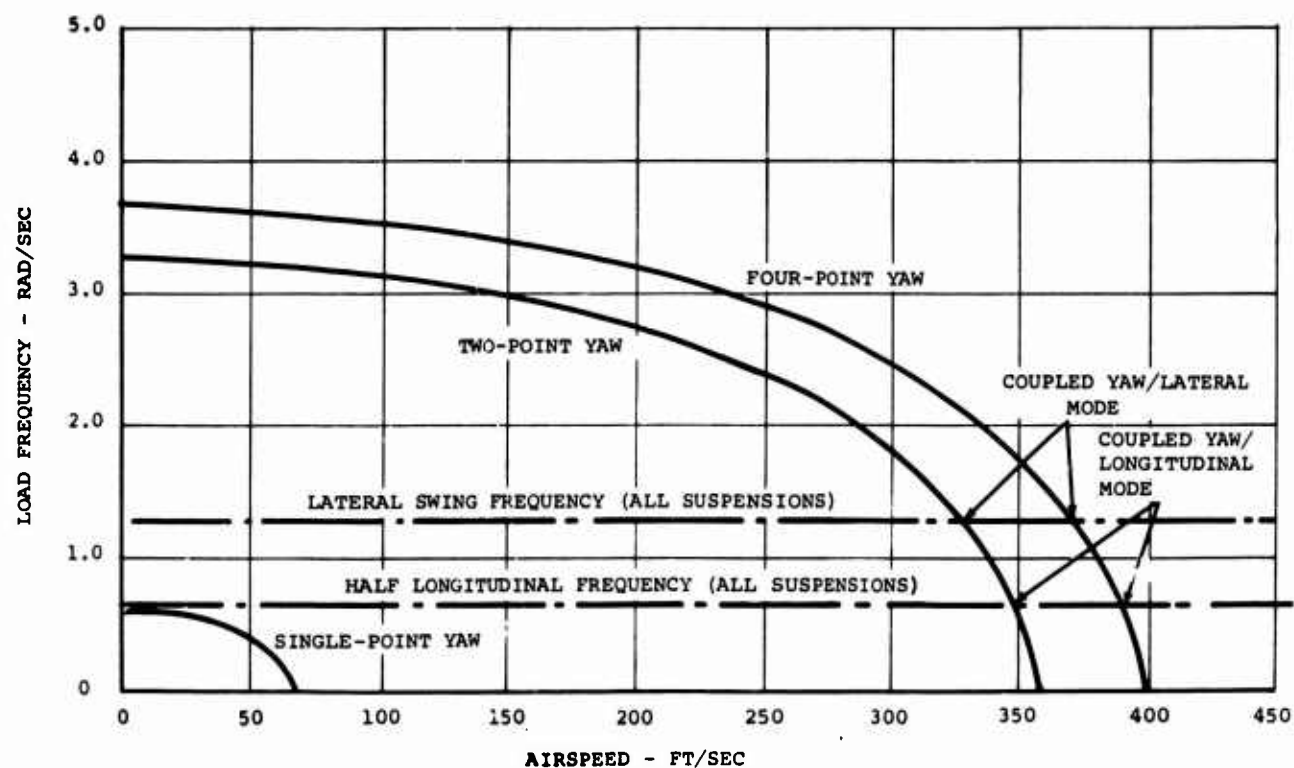


Figure 34. Load Oscillation Frequency

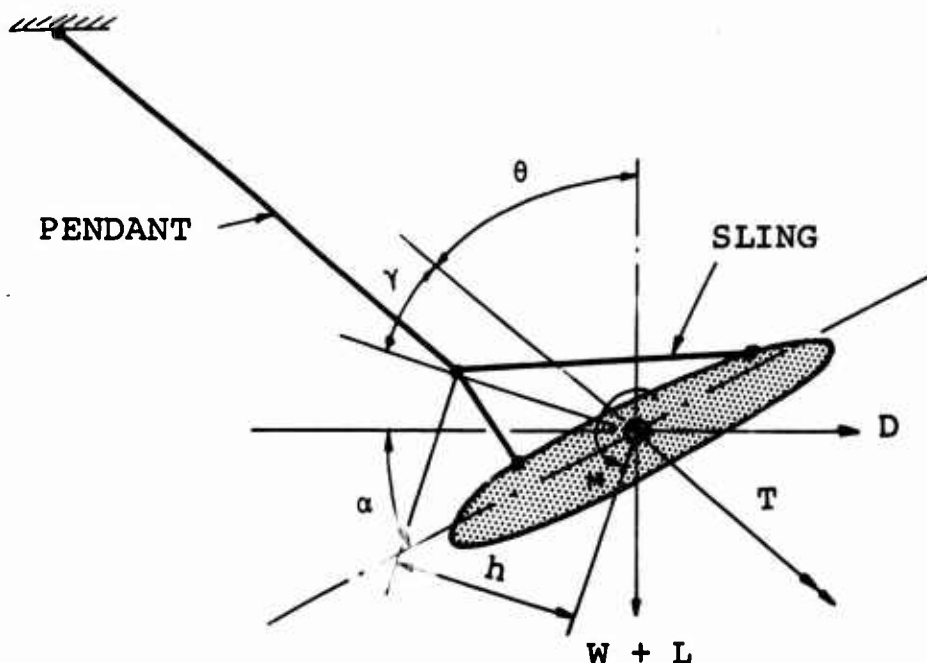


Figure 35. Forces Acting on Load in Pitch/Longitudinal Mode

For a given load, the stability may be altered by changes in sling length and in the relationship between the incidence (α) and the sling trail angle ($\gamma + \theta$). This relationship is actually a function of the static trim of the load; it has proved to be an extremely useful parameter in field trimming of loads, since it is a simple matter to change the length of the front sling legs. Experience has proved that nose-up static trim of a load is desirable; this is substantiated by the foregoing analysis since, by using a static nose-up trim, the incidence at a given forward speed is reduced, thus reducing both drag and $dC_D/d\alpha$ and hence increasing the stability.

It may be seen that the length of the suspension does not affect the pitch/longitudinal divergence mode. It becomes significant in the pitch/longitudinal oscillatory mode, since it affects the swing frequency of the load. Coupled pitch/longitudinal oscillations are common in external load operations. They are, in general, well damped and, therefore, not violent in behavior, although the resultant effect on the aircraft is such that forward speed has to be limited.

As previously stated, the geometry of parallel-leg multi-point suspension precludes any independent pitch motion of the load; for this reason, pitch divergence and pitch/longitudinal coupling problems do not exist. The spacing between pickup points on typical loads is not constant; the suspension legs will, therefore, not normally be parallel unless the two-point suspension with connecting beam is used.

Selection of the optimum suspension configuration based on stability criteria can be performed only if the aerodynamic characteristics of the loads are known. It is recommended that a study be made to determine the approximate aerodynamic characteristics of loads in the Army inventory and that a parametric analysis be made to determine the optimum suspension geometry to maximize the helicopter productivity.

LOAD SUSPENSION SYSTEMS SUMMARY

The following paragraphs summarize the results of the foregoing study of load suspension systems.

1. The four-point pickup system has significant advantages because the load can be pulled up to the fuselage, and thus can be considered an integral part of the aircraft structure. Improved methods of attachment are required to reduce installation time. When loads are suspended by cables from four separate points, a statically indeterminate system exists. To ensure effective system redundancy, stiffening of the suspension cables so that they are capable of taking compressive loads will be necessary. Shrouding the cables in tubes might offer one solution. However, for most of the materiel to be transported as external cargo, a two-point system shows promise of being effective.
2. The single-point system, presently in use on the CH-47A and similar aircraft, is considered to be the simplest, cheapest, and most reliable system for transporting external cargo of a general nature; e.g., rations, gas, ammunition, etc. If the cargo is fastened directly to the cargo hook without the use of a pendant, no restriction to forward speed is necessary. Development of the single-point system should be accelerated in order to increase productivity.

3. A single-point system using long pendants is considered to be practical for retrieving materiel from inaccessible areas. The cargo can be flown at low speed to a more compatible terrain and rigged with a shorter pendant for long-range transfer.
4. For cargo which is unstable during forward flight, the development of a two-point system fastened to the existing single hook is considered to be practical and relatively inexpensive.
5. Existing designs for cargo hooks are good. There is no reason why larger capacity hooks, using existing technology, cannot be designed. The area where further work is required is in the qualification testing of hooks. Where electrical continuity through swivel devices is required, the detail design and qualification of slip rings is the greatest problem.

SLINGS AND NETS

DISCUSSION OF SLING SYSTEMS

A review of the development and evolution of helicopter external load slings provides a significant insight into a little-known area of helicopter support equipment. Laymen often think that an external load can be attached to a helicopter by any means providing sufficient strength. Contrary to this belief, the sling is the most significant and potentially critical component used in external load operations.

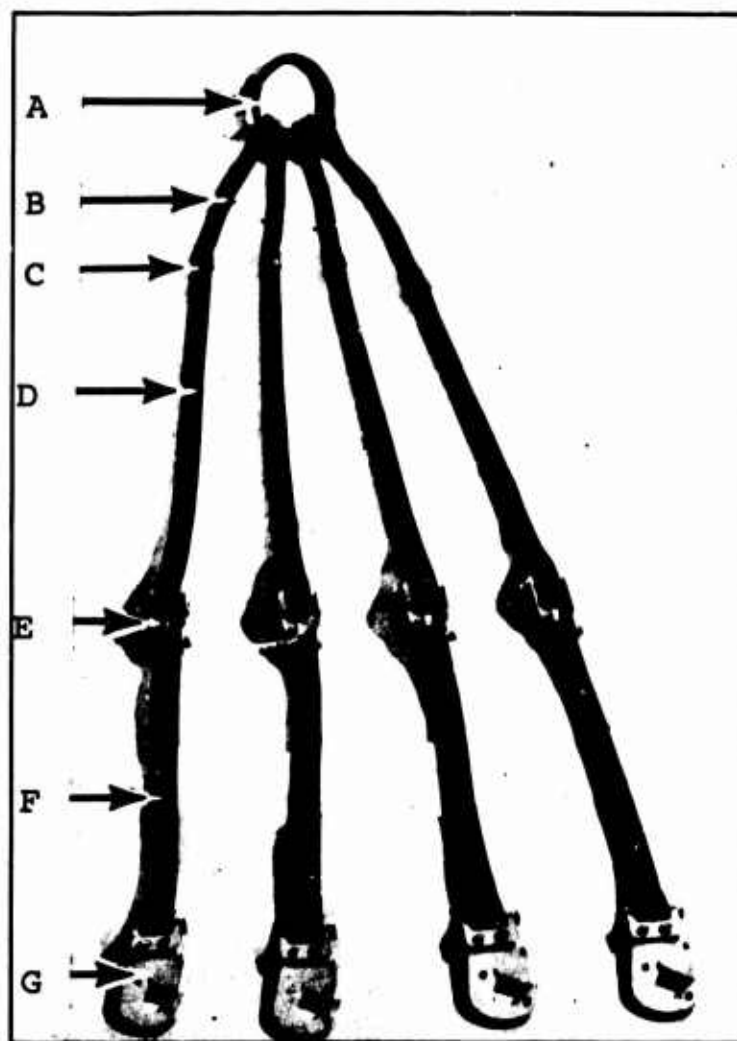
The advent of helicopters having lift capacities of between 2000 and 3000 pounds and complete cargo hooks paved the way for the transport of externally slung loads on an ever-increasing scale. It was obvious from the start that many loads within the gross weight range of a helicopter could not be loaded internally. At that time, fairly straight forward external loading was accomplished by connecting the load to the cargo hook with whatever material (rope, steel cable, nylon webbing, etc.) was available.

Some of the problems associated with this type of haphazard loading approach were: (1) the problem of determining the strength of materials in the field, (2) the problems of adapting whatever was available into a sling and attaching the makeshift sling to the load and to the cargo hook, and (3) the reliability of a basically haphazard technique.

The Army and the Marine Corps recognized, at a very early stage, the problems associated with external load slings and inaugurated programs to develop slings specifically for helicopters. The Army's efforts resulted in a highly flexible system called a Universal Cargo Sling Set.

Efforts of the Marine Corps in conjunction with the Aeroquip Corporation, resulted in the Marine Corps 10,000-pound Universal Cargo Sling, the basic building blocks of which are shown in Figure 36. This system is shown schematically in Figure 37.

Each of the two basic military types of helicopter external load slings incorporates desirable and essential features used in all slings.



- A - Nylon Lifting Ring (1 each) FSN 1670-823-5047)
- B - "D" Ring (4 each) (FSN 1670-823-5050)
- C - Nylon Keeper (4 each)
- D - Sling Leg or "A" Length (4 each) (FSN 1670-823-5449)
- E - Adjusting Ratchet (4 each) (FSN 1670-823-5045)
- F - Fixed Strap Assembly or "B" Length (4 each)
(FSN 1670-823-5048)
- G - Lifting Hook (4 each) (FSN 1670-823-5046)

General Logistics Universal Helicopter Sling,
(FSN 1670-823-5044)

Figure 36. Marine Corps 10,000-Pound
Universal Cargo Sling

The basic load slings include features which will possibly evolve for use in 12- to 20-ton cranes. Some of these features are presented below and will be discussed later in detail:

1. Overall lightness in sling weight
2. High strength
3. High sling flexibility
4. Long shelf and service life
5. Ease of rigging to the load and helicopter
6. Adaptability to irregular loads
7. Environmental capabilities
8. Freedom from periodic maintenance
9. Ease of inspection and replacement of worn or damaged components.

Both the Army and Marine Corps slings meet all the above requirements, but to varying degrees. Why then would there be a need to consider other types of slings? There are two answers to this question. First, most of the essential features of a helicopter external load sling are directly and inseparably related to sling capacity, so much so that good engineering practice dictates that slings, even so-called universal slings, be designed for a given maximum capacity. Second, in all areas of product development, sling hardware can be improved upon as a result of field experience and recent developments in subsystem technologies. The two-part answer to the above question leads to what could be called the second generation of helicopter external load slings.

CURRENT DEVELOPMENTS IN EXTERNAL LOAD SLINGS

Within the past five years, the turbine-powered helicopter has become a reality. With the increase in power has come a substantial increase in load-lifting capacity. Whereas many prior helicopters could carry external loads of up to 5000 pounds (in the case of one type, up to 8000 pounds), the turbine-powered models now carry up to 20,000 pounds. These larger capacities outstripped the capabilities of existing external load slings.

Some modifications have been incorporated into the Army Universal Cargo Sling Set in order to meet the new capacity demands. These consisted of paralleling endless loops to increase sling leg capacity. These endeavors have met with formidable drawbacks in the areas of logistics requirements

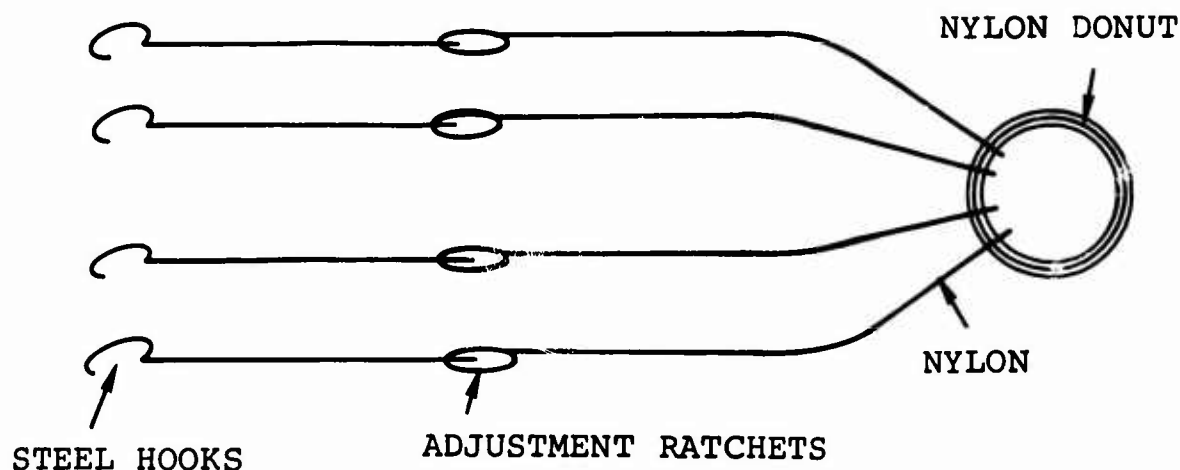


Figure 37. Schematic of Marine Corps 10,000-Pound Universal Cargo Sling

(30 to 50 endless loops required for a sling on certain loads), disproportionate rigging times (several man-hours for some loads), and additional hardware requirements (new high-capacity nylon donuts required).

Because the drawbacks listed above imposed too great penalties, the most direct approach to the situation was obviously to develop a new family of 20,000-pound-capacity slings. A new approach was, therefore, undertaken by both the Army and the Marine Corps. In addition to increasing the sling capacity, each Service used the opportunity to incorporate design refinements resulting from their particular operational experience and beneficial to their specialized requirements. It is noteworthy that the separate requirements of the two services resulted in two completely different sling configurations. U. S. Army and U. S. Marine Corps sling configurations are shown in Figures 38 and 39.

SLING DESIGN REQUIREMENTS

Helicopter external load slings have numerous requirements which govern design. The design requirements include margin of safety, reliability, durability, flexibility, compatibility with existing helicopter release hooks, adaptability to irregular loads, simplicity of use and reuse, field repairability, and spring rate.

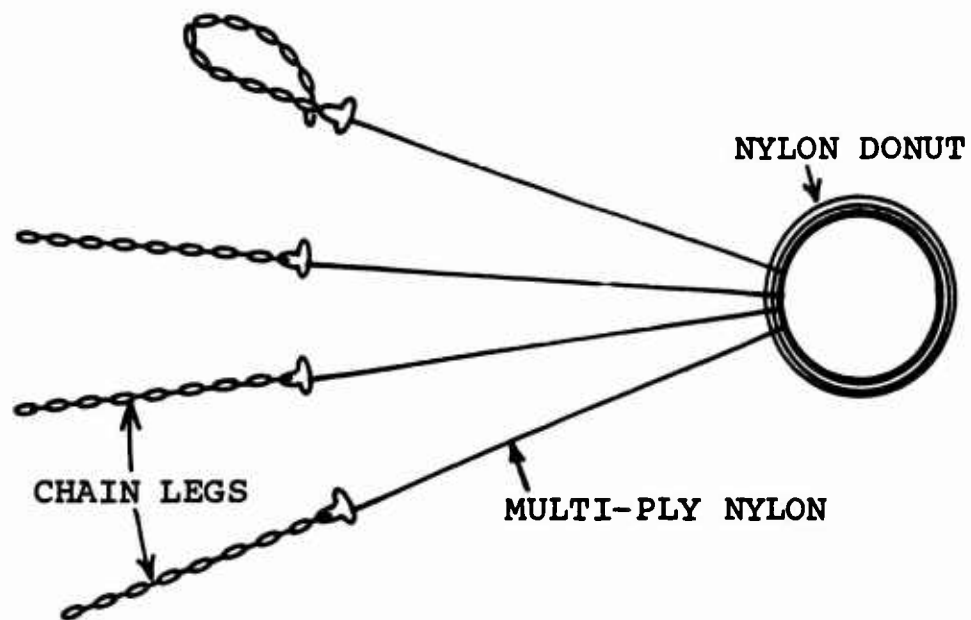


Figure 38. Schematic of Army 20,000-Pound Nylon and Chain Leg Sling - MCN-4920-M54-3174

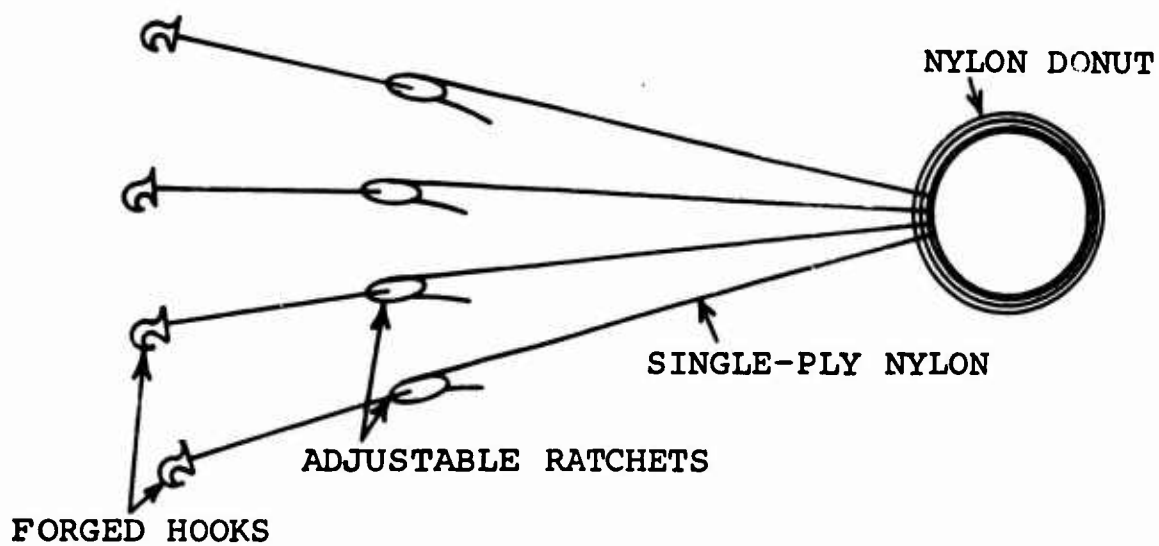


Figure 39. Schematic of Marine Corps 20,000-Pound Cargo Aerial Delivery Sling - MIL-S-82113(MC)

Margin of Safety

This is the amount by which the inherent sling capacity exceeds the maximum static load which will be carried. This strength margin is designed-in to compensate for increases in individual sling-leg loads caused by sling-leg angles other than the vertical, unequal loads due to sling redundancies, alternating loads, external load drag in forward flight, and centrifugal force effects in maneuvers. It also allows for possible sling strength deterioration caused by wear, damage, age, or improper rigging. The 10,000-pound-class slings were designed with factors of safety of 4 to 1. Field experience and the need for compatibility with other design requirements have resulted in a reduction in factor of safety to 3 to 1 on the 20,000-pound-class slings. At this time, 3 to 1 appears to be the safe limit for both present slings and those of the forthcoming 40,000-pound class.

Reliability

The necessity for high reliability is obvious. Reliability is the fundamental quality underlying the universally accepted use of nylon webbing as the basic helicopter external load sling material. Nylon webbing can be visually inspected with a high degree of confidence. The wide flat shape of the webbing and its detailed makeup combine to produce an element which virtually shows its strength. Even inexperienced personnel can be briefed on the proper methods of inspection in a short period of time.

Durability

The sling must not possess any restrictions against use throughout some specified extreme operating environment for helicopters (such as temperatures of -65°F to +125°F and relative humidities of 0 to 100 percent). It should require no periodic maintenance during storage or use, except that caused by wear or damage.

Flexibility

Maximum flexibility in all areas of the sling except the nylon donut is essential to ensure ease of rigging to the load, speed of hookup to the helicopter, and minimum storage space requirements. The nylon donuts should be

of small diameter and heavily impregnated to produce a semirigid element which will not bend excessively when passed through a spring-loaded cargo hook keeper.

Compatibility with Existing Helicopter Release Hooks

The presence of single-point hook release systems on helicopters dictates that all multiple-leg slings terminate at their upper ends in a single stiff ring. Suspension of loads for multi-point systems may be made by using multiple slings.

Adaptability to Irregular Loads

The sling should be compatible with as wide a variety of irregularly sized and shaped loads as can be anticipated. The Army, with its nylon- and chain-leg sling, has created a system which can handle up to 3-foot differences in sling-leg length requirements. Lifting eyes or hooks are not required on the load, since the chains can be looped over beams, axles, and the like. In addition, chains at the load end of the sling prevent chafing in cases where the parts of the sling (in addition to the end connection) must be in contact with the load. The Marine Corps, by its choice of configuration for both the 10,000- and 20,000-pound-class slings, implies that most Marine Corps materiel will have lifting eyes and shackles, but will require up to 10-foot differences in sling-leg length.

Simplicity of Use and Reuse

This means that the final product should, by its very form, indicate precisely how it should be rigged and unrigged from loads. It must lend itself to easy and quick rigging, and there must be no requirements for tools of any type to accomplish either the rigging or the unrigging processes. This aspect of sling design becomes extremely important with the advent of the flying-crane concept. Successive lifts of a large number of loads over a short distance can only be accomplished efficiently with prerigged loads and the repeated use of a small number of rapidly rigged and unrigged slings. It should be noted that the Army 10,000-pound universal sling does not meet the unrigging requirements, since when two loops are strung together and then loaded, they become difficult

to separate.

Field Repairability

Of necessity, all helicopter external load slings are composed of a group of components, each designed for a specific function. As might be expected, the rate of wear and susceptibility to damage vary with the different components. A most desirable feature is that of field disassembly and interchangeability of hardware, sling-leg webbings, and nylon donuts. Both the Army and Marine Corps 20,000-pound-class slings possess these features.

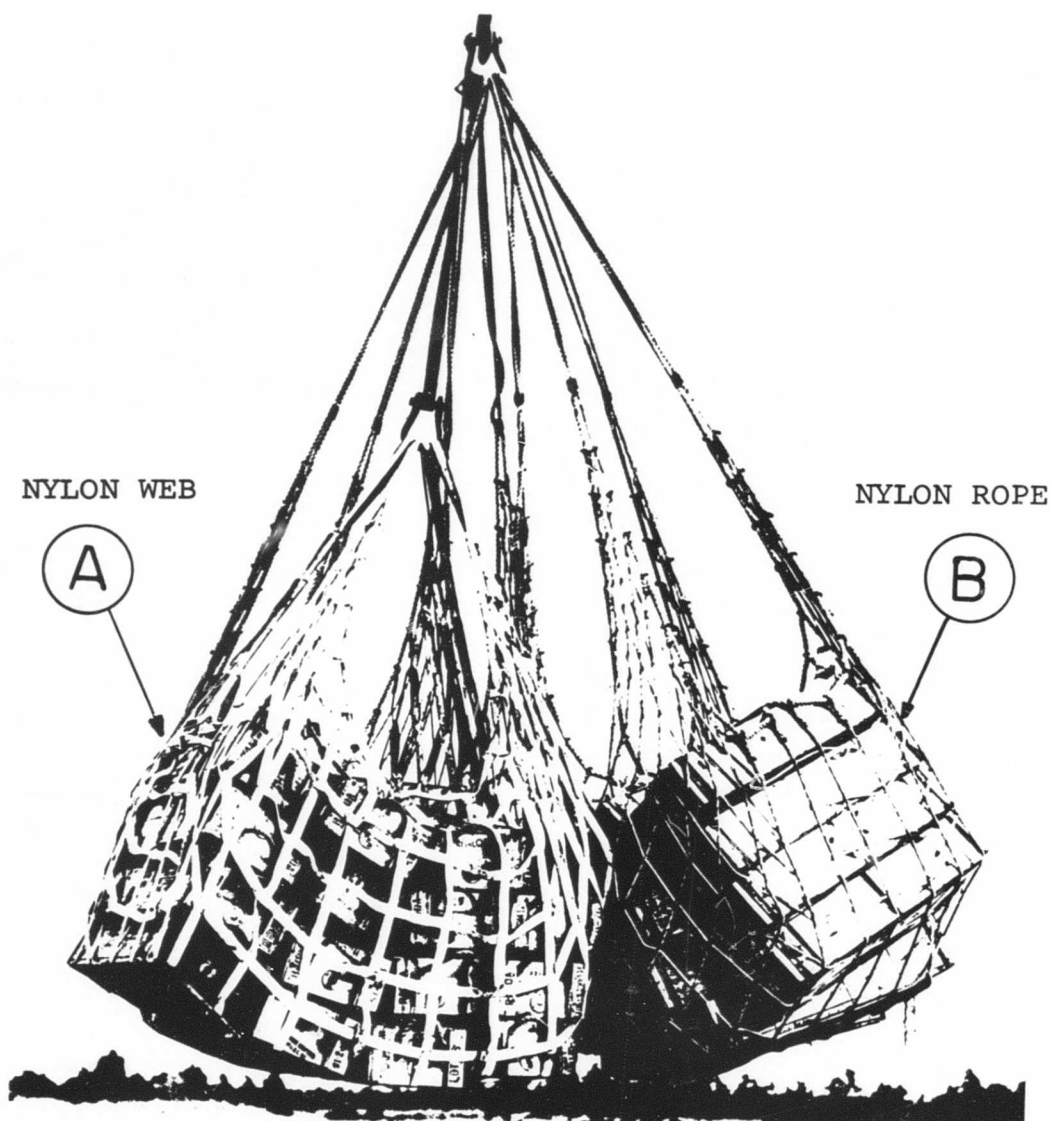
Spring Rate

An item which up to now has not been considered as a design requirement is the rate of stretch, or spring rate, of slings under load. Spring rate controls the natural frequency of the sling/load system. It is desirable to have sling system natural frequency well below the one-per-revolution vibration excitation frequency of all helicopters (refer to VERTICAL BOUNCE, discussed on page 123). Since this excitation frequency varies from helicopter to helicopter, slings should be designed with a spring rate which will produce a natural frequency no higher than 2.5 cycles per second with the design maximum load attached.

CARGO NETS

Cargo nets provide a simple means to restrain and support slung loads. See Figure 40. Almost all experience with nets as slung load carriers on helicopters has been confined to loads of less than 1.5 tons per net. The feasibility of handling much larger loads in simple nets has not been established, and it is not likely that the use of simple nets for 5- to 10-ton loads will be satisfactory because of the increased severity of crushing loads which may be imposed on the cargo.

As nets are picked up, the items around the edges of the load tend to shift upward and inward (see Figure 41). Items in the center tend to sag, and the bottom of the load tends to assume a hemispherical shape. Destructive stress concentrations may occur during pickup, during flight, or upon touchdown; or stress may result from falling when drawstring tension is



NYLON WEB AND NYLON ROPE NETS CLUSTERED

Figure 40. Typical Netted Loads

released. In order to reduce the crushing forces imposed by nets, long drawstrings can be used. The gains from lengthening the suspension lines can be illustrated by the hypothetical examples shown in Figure 41. Assume that the top of a 10-ton load is a square with 8-foot sides. If the focal point is 4 feet above the top of the load, the horizontal crushing force on each side of the load during a 1.0g pullup is about 5 tons. If this distance is increased to 8 feet, the crushing force per side is reduced to about 2.5 tons. When the use of long suspension lines is not acceptable, the other devices described in following paragraphs can be used to reduce the crushing forces on the cargo.

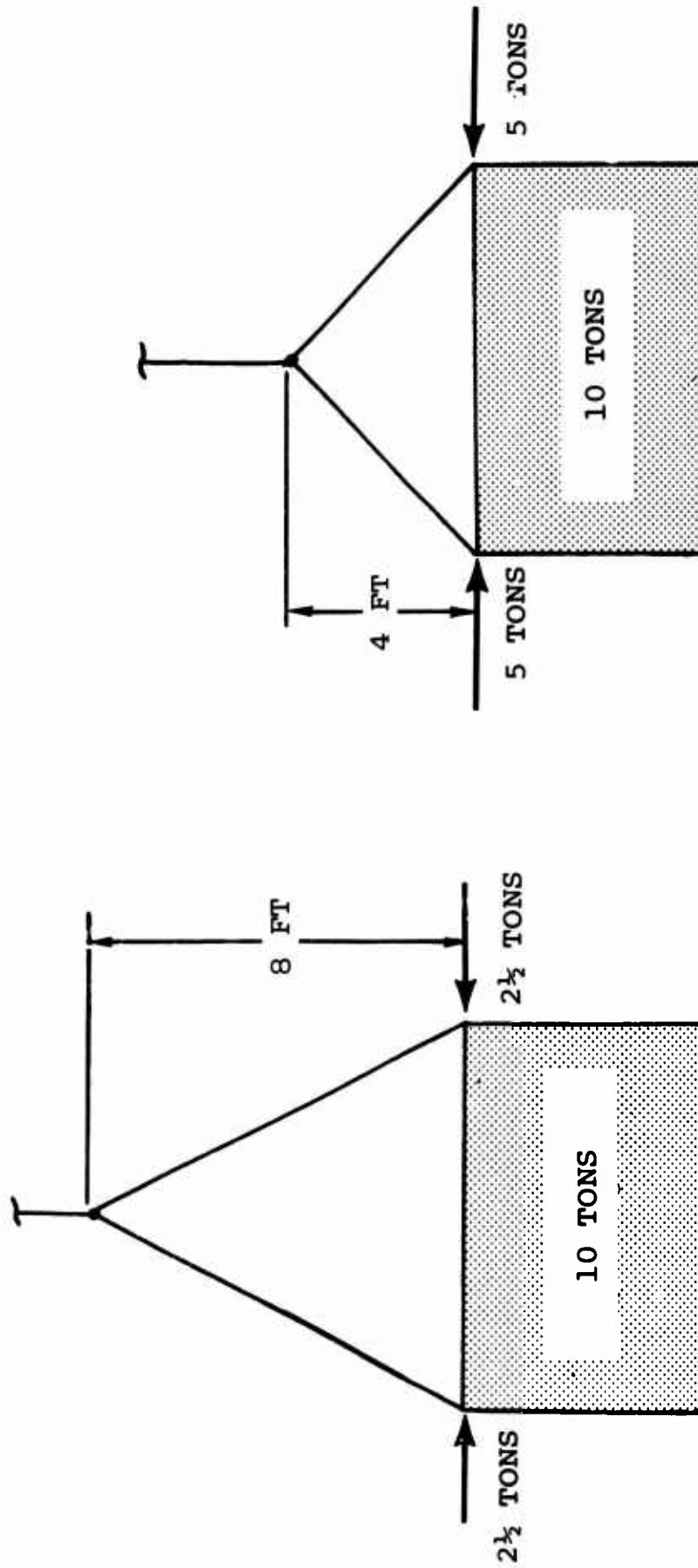


Figure 41. Effect of Sling Length on Crushing Forces

A part of the load weight in the net and drawstring can be transferred to a line or rod extending from the hook through the center of the cargo and fastened to the net. As much as 50 percent of the weight can be transferred to the center suspension with a corresponding reduction of the crushing forces. The net design would require a strong point of support at the center to accommodate the additional support. See Figure 42. Nets which do not extend well above the top of the cargo may require additional restraints to prevent cargo from falling out.

Cargo can also be protected from a greater part of the crushing forces by the use of spreader frames. The use of such frames will reduce but will not eliminate the dislocation of items in stacks. See Figure 43. A system made up of a platform, a center suspension line, a net designed for side and vertical restraints, and simple straps across the top of the load could be used to prevent dislocation of stacks and serious crushing forces and to restrain the cargo upon delivery. Typical dimensions, weights, and capacities of currently available helicopter cargo nets and release hooks are given in Tables I and II.

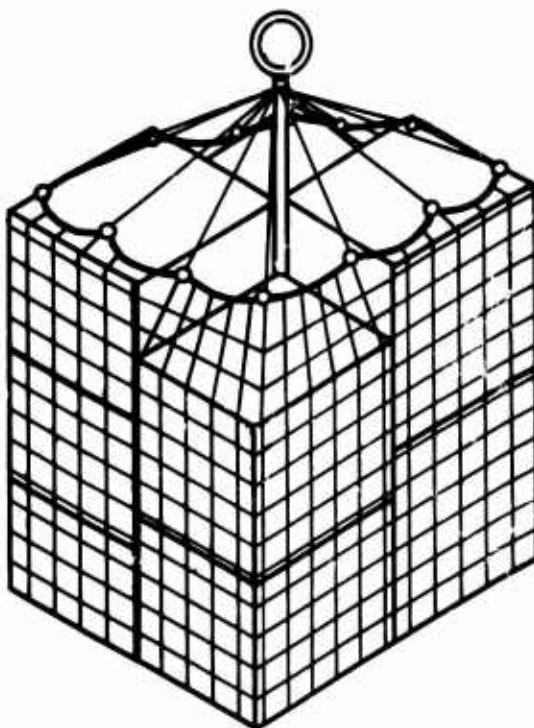


Figure 42. Net with Center Rod

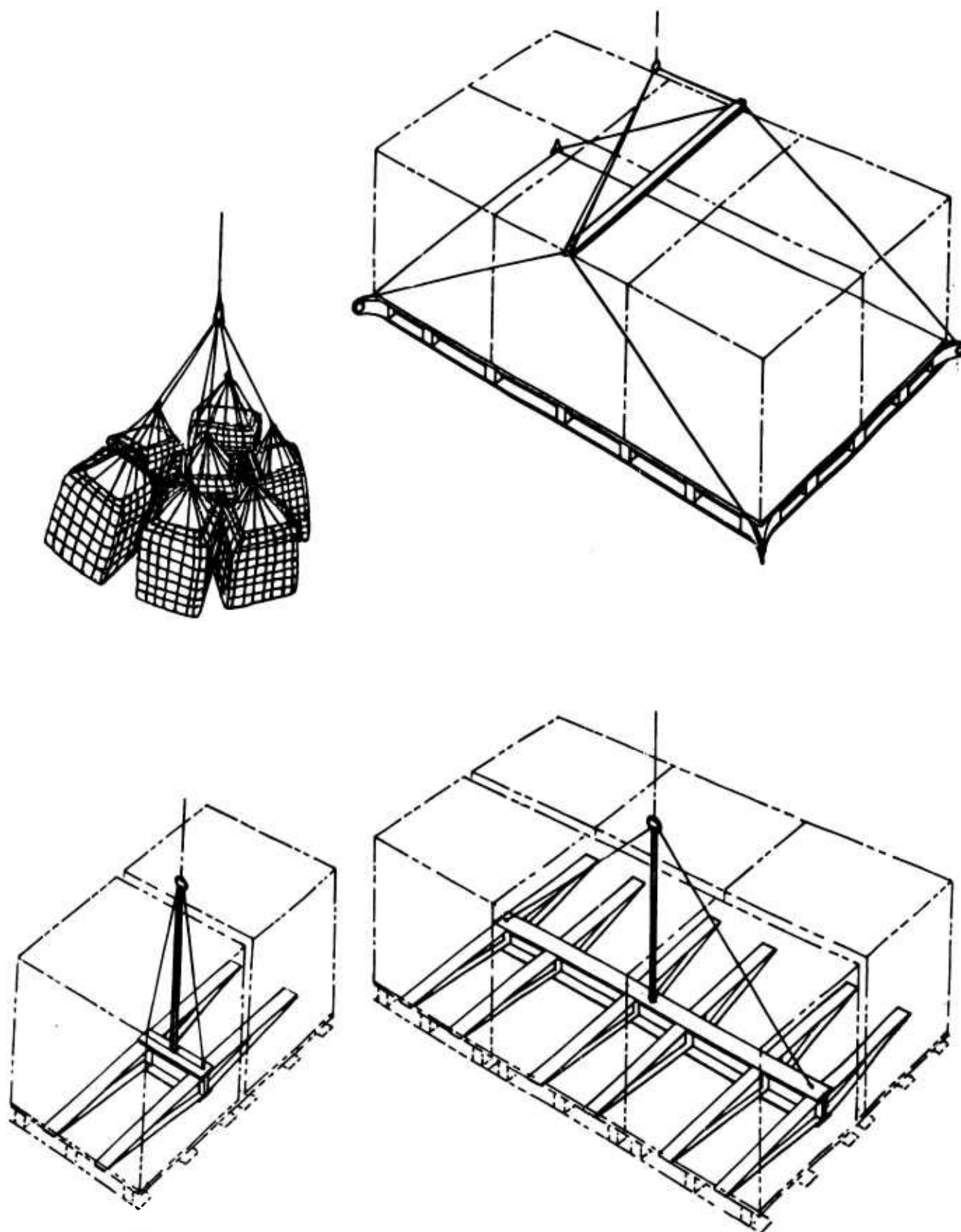


Figure 43. Protection of Load by Use of Spreader Frame

TABLE I
HELICOPTER NETS

Part No.	Description	Size	Made From	Operating Capacity (lb)	Weight (lb)
SP-4135-1	Sling Net	10-ft octagon	1/8-in. cable	2,500	21.8
SP-4136-1	Sling Net	14-ft octagon	1/8-in. cable	5,000	35.5
SP-4137-1	Sling Net	14-ft octagon	5/32-in. cable	10,000	68.5
SP-4138-1	Sling Net	15-ft octagon	1-3/4-in. nylon webbing	10,000	32.0

The above cable nets are available with stainless steel cable.

TABLE II
HELICOPTER CARGO RELEASE HOOKS

Part No.	Description	Operating Capacity (lb)	Size (in.)	Weight (lb)
SP-4231	Self-Loading Mechanical Cargo Hook	1,000	7½ x 9	3.58
SP-3094	Cargo Hook	2,500	6 x 8	5.25
SP-4224-1	Self-Loading Cargo Hook	2,500	8 x 8	6.95
SP-4061-1	Cargo Hook	2,000	7 x 9	6.80
SP-4100-1	Cargo Hook	4,500	7 x 9	7.15
SP-4405-1	Self-Loading Cargo Hook	4,500	9 x 10½	10.20
SP-4070	Cargo Hook	6,000	7 x 9	9.90
SP-7109-1	Self-Loading Cargo Hook	6,000	9 x 11	14.00
SP-7102-1	Self-Loading Cargo Hook	10,000	12 x 14	23.70
SP-7070-1	Self-Loading Cargo Hook	20,000	11½ x 14½	40.20

Eastern Rotorcraft Corporation

HOIST SYSTEMS

HISTORY OF HOIST SYSTEM DEVELOPMENT

The original helicopter hoist systems were developed from hoists used by the Navy to rescue men from the water. The utility of such systems led to their application to the lifting of materiel, whereupon the lift capacity of existing systems became inadequate and systems of larger lift capacity were required.

The first evaluation of a cargo hoist system was made on the S-60 - a helicopter conceived in the flying-crane configuration. The evaluation of the S-60 hoist system indicated that such systems were feasible, practical, and more versatile than fixed external suspension systems. The practicability of the S-60 hoist system led to its inclusion in the CH-54A flying crane.

The CH-54A single-point hoist system has 100 feet of winch-operated cable which, as shown in Figures 44 and 45, permits a high hover over loads and subsequent winching of the load to the helicopter. The prime limitation of the system is the tendency of loads to rotate and oscillate in forward flight, which necessitates a reduced airspeed.

Airborne four-point hoist systems were the natural development of the existing limited-travel four-point suspension system on the CH-54A helicopter. The four-point hoist system, which is now under evaluation by the Army, was introduced to expand the capability of the original four-point suspension system. However, it does not incorporate the automatic safety and redundant features discussed under MULTI-POINT SUSPENSION in the LOAD SUSPENSION SYSTEMS section (page 21).

WINCH CABLES

The single element which governs the design of a winch is the cable. Cable diameter fixes drum diameter, and cable length determines drum width. Existing helicopter winches, of which the majority are utility rescue types, employ small-diameter 1/4-inch cables. A cable of this diameter does not present bending stress problems due to winding the cable on the drum. A drum-diameter-to-cable-diameter ratio of 20:1 is used; it

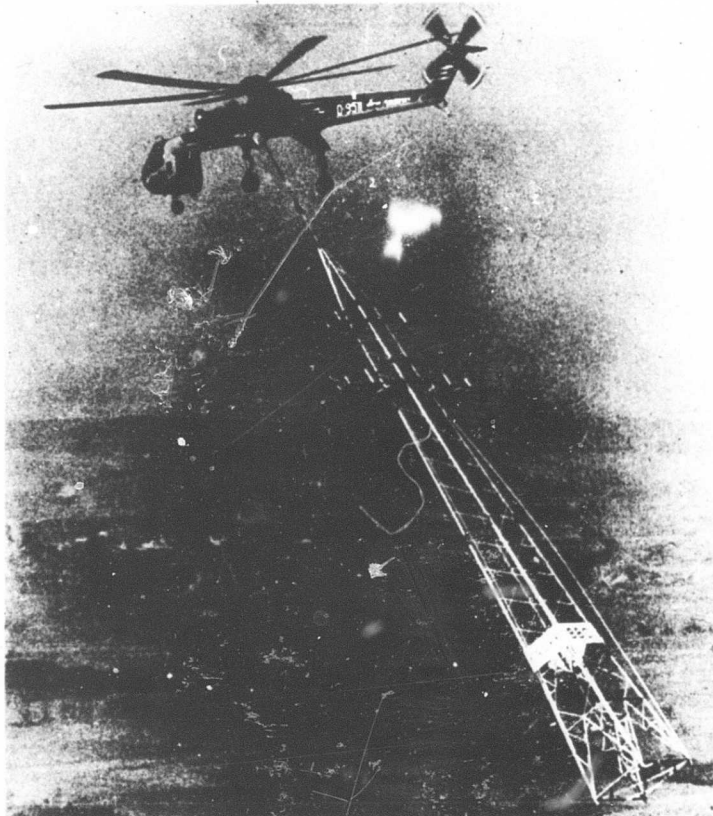


Figure 44. CH-54A Airlifting Pylon



Verti-Flyte Magazine

Figure 45. CH-54A Single-Point Hoist System

is the same ratio as that used in aircraft control system flexible cable runs. When semiflexible cables are used with electrical conductors, higher ratios are used; e.g., the Model 64 winch (All-American) has a ratio of 59:1; it uses a 3/10-inch-diameter cable with a 7000-pound maximum static capacity.

When larger diameter cables are used, consideration of bending stresses in cables wound on the drum is of great importance (refer to Figure 46). Using 1-inch-diameter 6 x 19 cable (tensile strength, 90,000 pounds) with a ratio of 50:1, bending stresses with equivalent tensile loads of 5000 pounds are obtained. If the ratio is reduced to 20:1, the equivalent load increases to 13,000 pounds.

On a conventional-type winch, where the cable on the drum carries the tensile load, the bending load is additive, thus effectively reducing the cable capacity and introducing a severe fatigue condition. For semiflexible cable and cable with internal conductors, the acceptable drum-cable diameter ratio may well exceed 60:1. However, in the absence of any specification covering this type of cable, the actual drum requirements are yet to be established.

A secondary effect of increased drum size is increased gear ratio between the motor and drum. The combined increased component weight affects the system weight.

If a single winch with a capacity of 40,000 pounds is required for the heavy-lift helicopter and an electrical load release is fitted (necessitating conductors running through the cable), the cable diameter would be approximately 1-1/2 inches. Use of a 60:1 drum-cable diameter ratio would then result in a drum with a 90-inch diameter.

It should be noted that new "high-strength" cables with reduced diameters are usually stiffer and, therefore, require larger drums than conventional 6 x 19 cables. The increase in drum weight may more than offset the weight reduction in the cable.

CONVENTIONAL WINCHES

The conventional winch, as typified by the CH-54A single-point winch (Figure 47), consists of a hydraulically driven drum on which the cable is wound. The cable on the drum is under tension, and the load is transferred through the drum to the drum bearings, allowing the cable on the drum to behave,

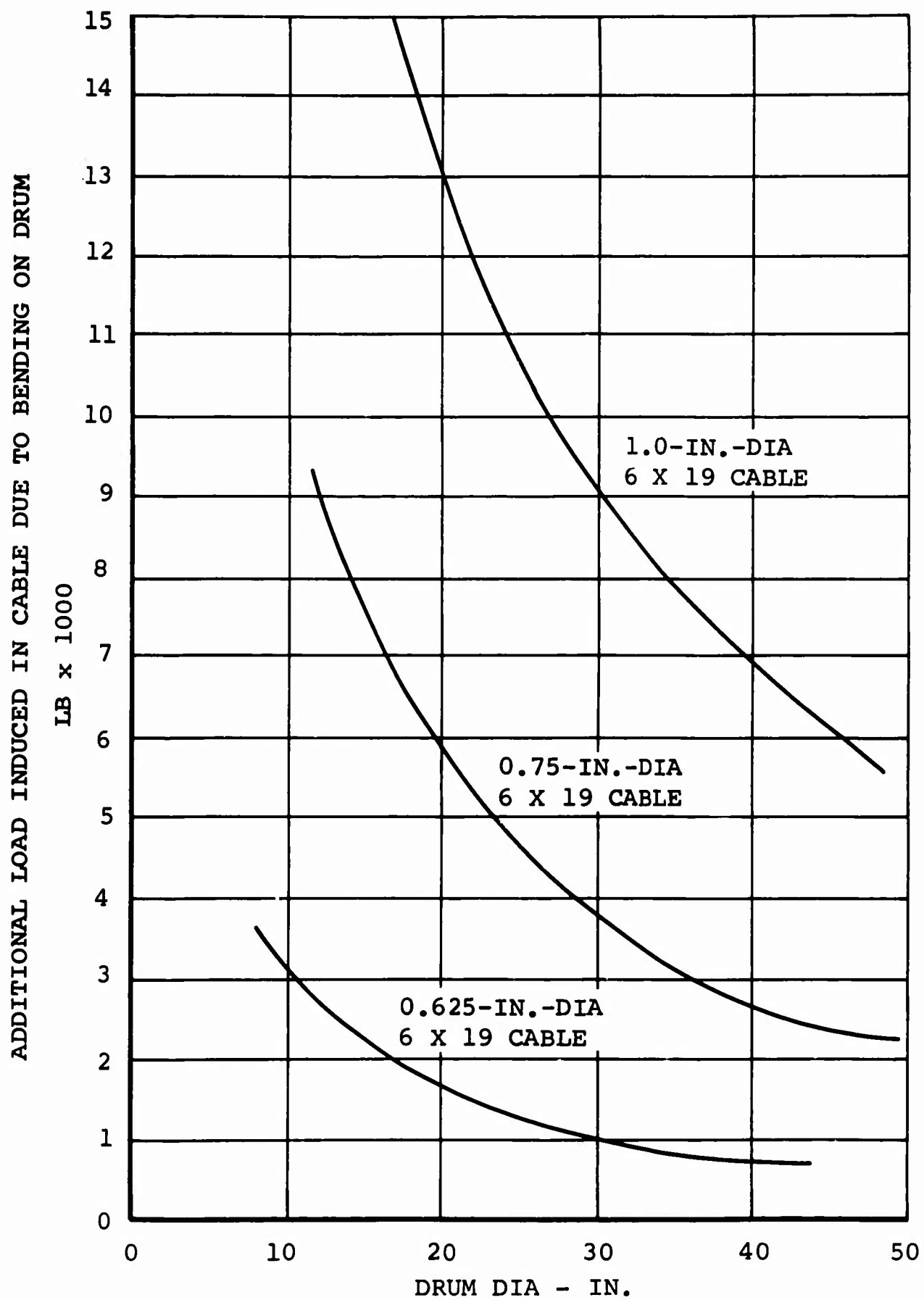


Figure 46 . Effect of Drum Diameter on Cable Stre

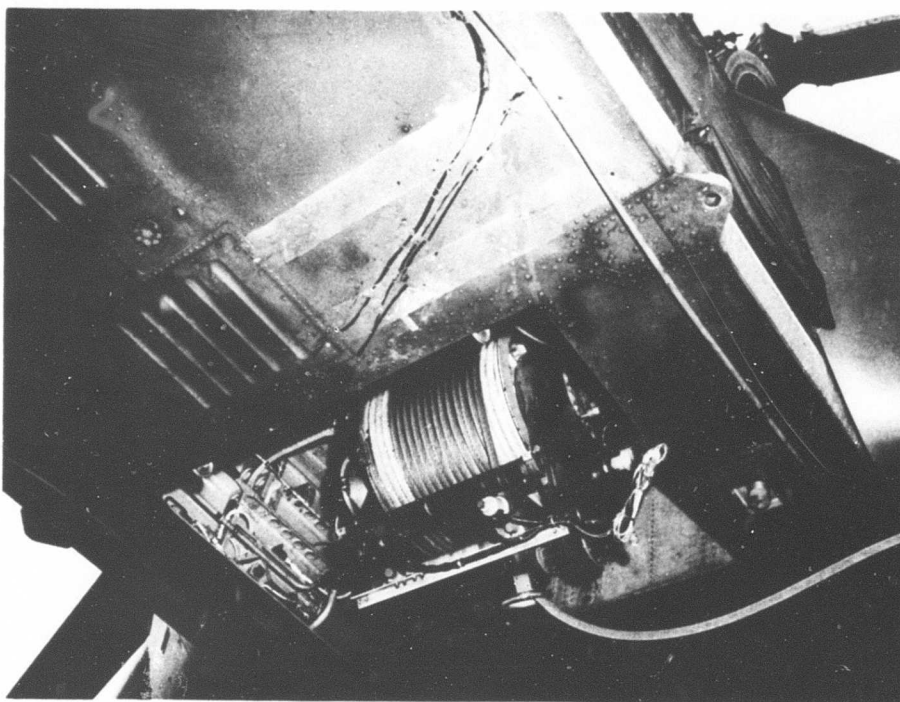


FIGURE 47. CH-54A Single-Point Winch

structurally, like a beam. It has been found that if the cable is wound on itself under load, chafing occurs, with a resulting reduction in cable life; to prevent this, a level wind is usually fitted. A level wind is a device that guides the cable onto the drum in a single layer. Such a device is shown in Figure 47. If the cable to be used is very long, the drum must be long and, since it must carry supporting loads, the weight increases. Furthermore, if the winch is rigidly fixed to the aircraft, a change in cg position occurs during winching, thus requiring pilot correction.

Another problem with rigidly attached winches is that if the load does not hang vertically below the winch, the cable is subjected to bending moments at the fairlead. The previously mentioned cg shift may be corrected by hanging the entire winch on a universal joint. This, however, necessitates excessive clearance between the winch and the surrounding aircraft structure and actually increases the problem of the cable's bending through the fairlead, as illustrated in Figure 47.

In an attempt to reduce system bulk and weight, capstan-type winches have been developed and are described in detail in following paragraphs.

CAPSTAN WINCHES

The capstan-type winch eliminates the load in the cable on the storage drum by performing the winching function on an auxiliary capstan drum. A typical capstan winch is shown schematically in Figure 48. The CH-54A capstan-type, four-point winch is shown in Figure 49.

In the capstan winch, the cable does not move laterally during reeling, but instead enters a guide affixed to the capstan drum. The guide is narrow and structurally efficient. The capstan also makes the winch ideally suited to universal mounting. The surplus cable is wound on the takeup drum, and since there is no load in the cable at this point, it is acceptable to wind the cable on itself, thus reducing the drum width.

Existing designs of capstan winches subject the cable to reverse bending, thus accentuating the cable fatigue problem, particularly if electrical conductors are built into the cable. The Breeze Corporation, manufacturer of the CH-54A four-point capstan winches, indicates that the reverse bending condition could be eliminated in a new design, but such a system is not at present available.

Since the capstan principle dictates that the cable must negotiate a series of pulleys and drums, the cable is prone to jumping off the pulleys. This occurs on release of the load, when cable tension is suddenly released. Good detail design practice can eliminate the problem by careful placement of guards.

The open design of the capstan winch exposes the mechanism to the elements - an undesirable condition in helicopter installations, where contaminants are stirred up by the rotor downwash. Enclosure is feasible, but it will add weight.

SINGLE-POINT HOIST SYSTEMS

The basic purpose of a hoist system is to enable the helicopter to acquire a load from an inaccessible place, or to stand off from the load to alleviate downwash problems. Another use

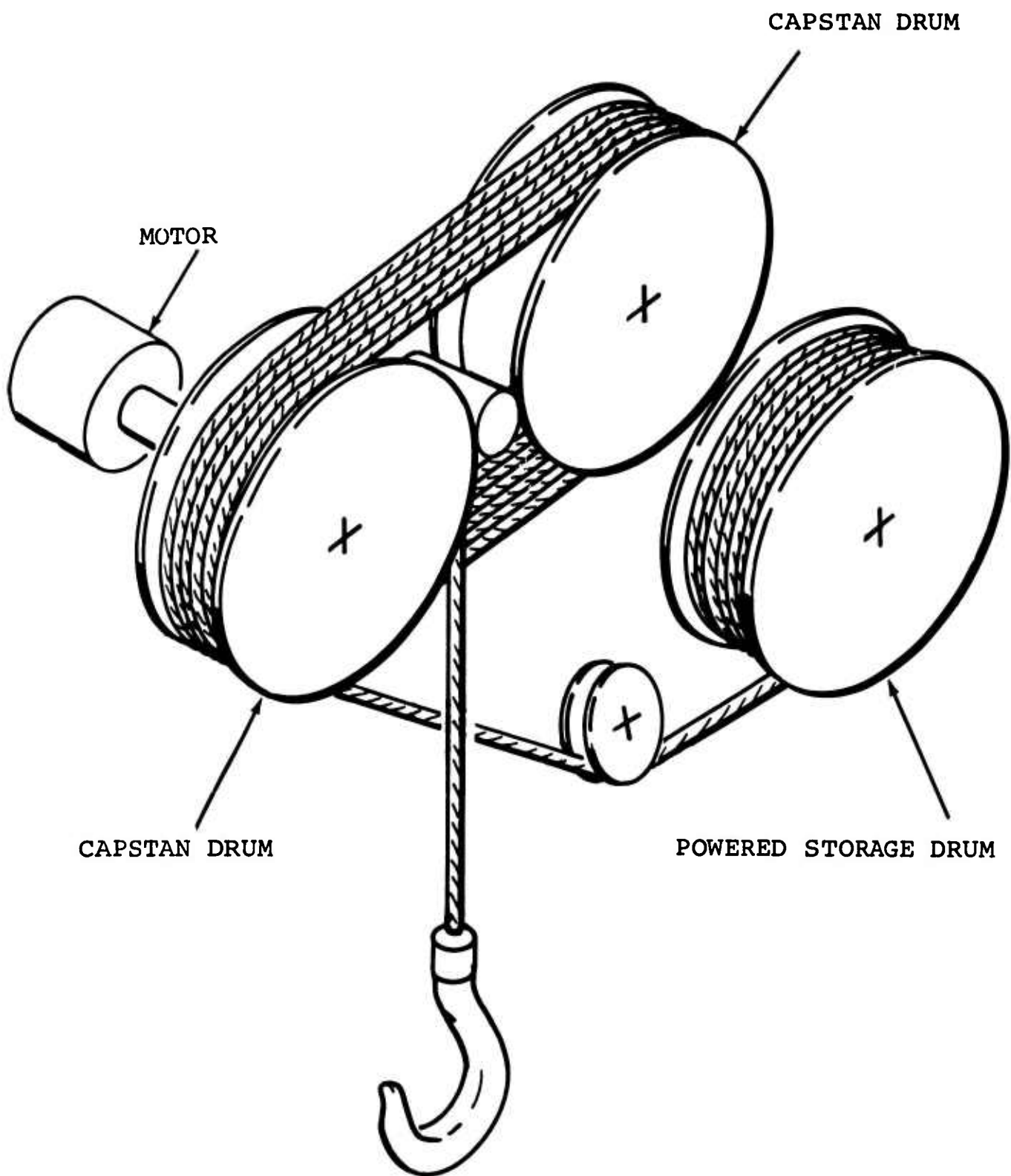


Figure 48. Schematic of a Capstan-Type Winch

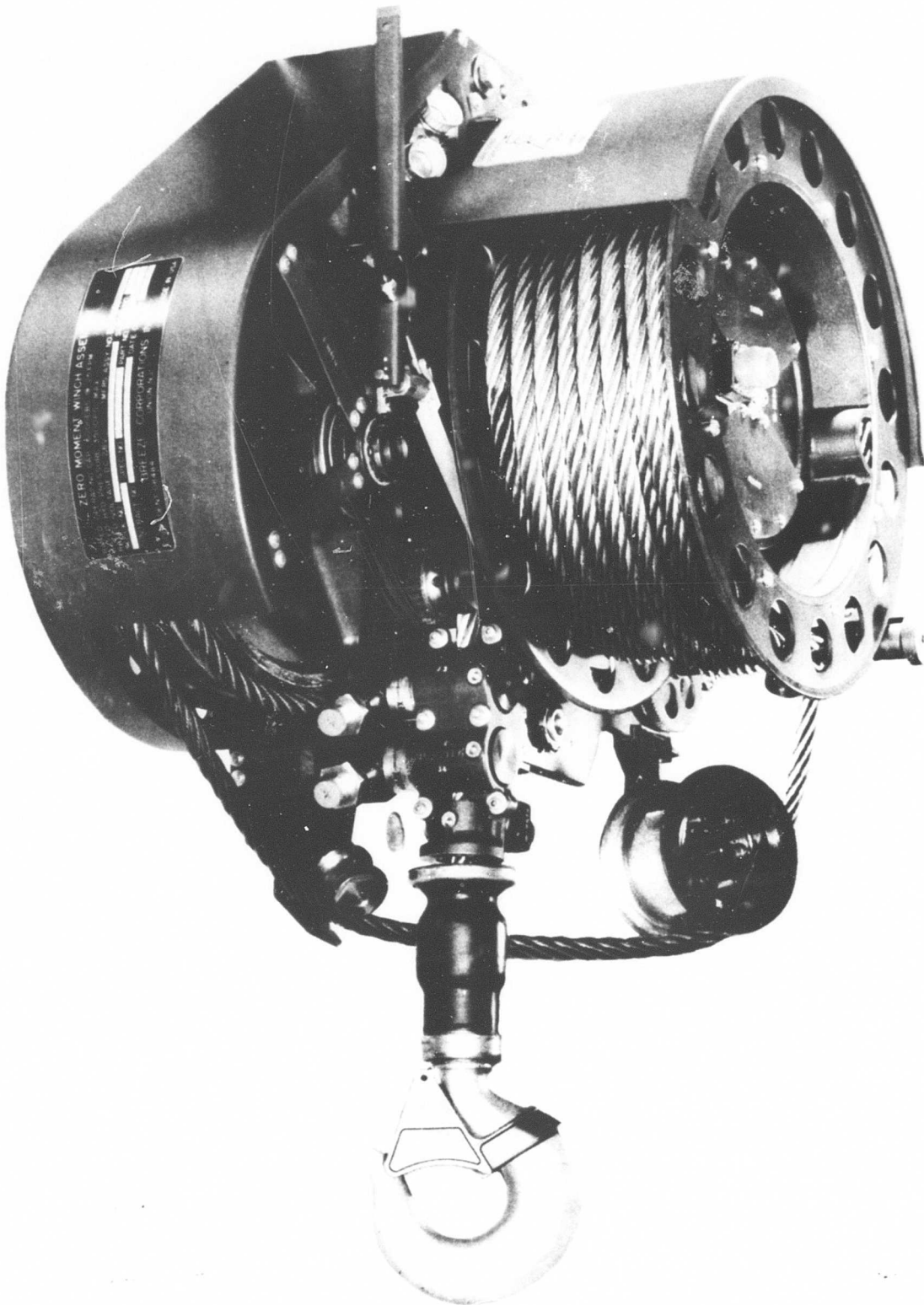


Figure 49. Capstan-Type Winch - CH-54A Four-Point Hoist System

occurs in the vertical replenishment of warships operating in high-sea conditions where the load is heaving and rolling with the ship. Such a system is fitted to the UH-46 helicopter shown in Figure 50. It may be argued that these tasks can be performed by using a long, fixed pendant attached to a belly hook. There are two reasons why this is not done. First, in many cases, the crew of the helicopter does not know in advance how much pendant is required. Second, and more important, it is sometimes difficult to fly with loads on very long suspensions.

Analysis of the Vertol 107 helicopter hovering with large loads on long suspensions (for a logging operation) indicated an unstable swaying mode in hover (refer to STABILITY IN HOVER AND FORWARD FLIGHT, on page 145). This instability has a long periodic time which, while making it possible for the pilot to fly the helicopter, still produces an unpleasant sensation. Stability in forward flight depends on the actual load. If the load is aerodynamically stable, the long suspension is not usually detrimental; however, for unstable loads, the cruise speed may be severely limited. One problem with long suspensions is at least partly psychological; that is, the tendency for loads to make large excursions at the end of the pendant. Operational helicopter crews are not accustomed to seeing this and tend to fly at reduced speeds, even though the actual angular excursions of the pendant may be the same as those experienced with a short pendant and considered acceptable (see Figure 51).

An important difference between long and short pendants, however, is that although the loads on the helicopter may be of the same magnitude, the frequency of the oscillations is different. Long suspensions give rise to low-frequency motions which tend to be very uncomfortable. This is discussed in STABILITY IN HOVER AND FORWARD FLIGHT referenced above.

One of the most useful attributes of a hoist system is to enable the helicopter to acquire a load on a long line and then to shorten it to the optimum length for high-speed flight. The CH-54A helicopter is fitted with a single-point hoist system which utilizes a winch of 20,000-pound capacity equipped with 100 feet of cable to permit a high hover over loads. A load isolator was fitted to compensate for anticipated vertical bounce of the load; subsequent tests proved this to be an absolute necessity for lifting maximum-weight loads. Load vertical bounce and load isolators are analyzed in detail in



Figure 50 . UH-46 Single-Point Hoist System

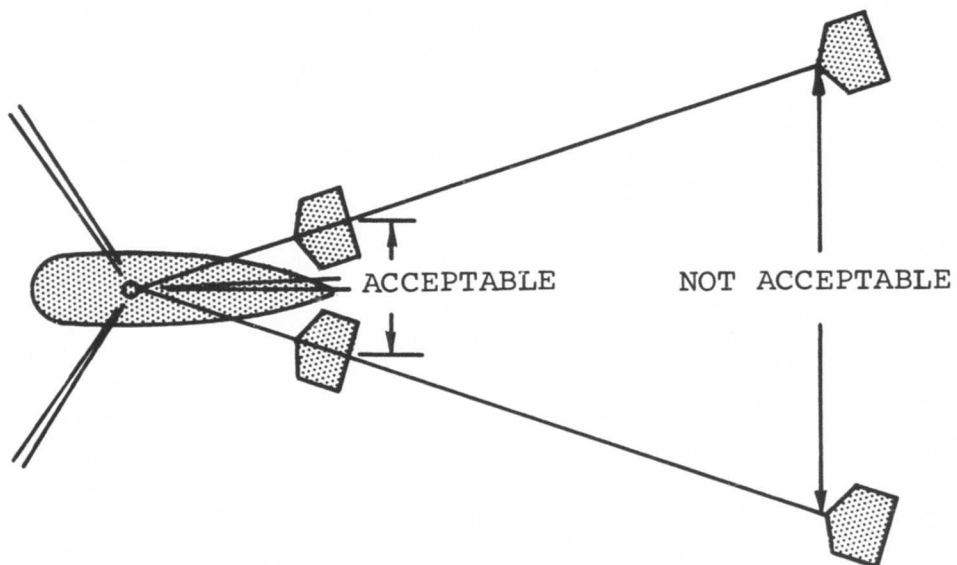


Figure 51. Effect of Suspension Length
on Acceptable Load Oscillation

a later section under the heading VERTICAL BOUNCE. The system (which weighs approximately 980 pounds, excluding cable) was originally fixed to the helicopter. Subsequently, the winch was made removable, which increased the capability of the basic aircraft when the system is not utilized.

The hoist system is mounted directly under the main transmission; it consists of a large hydraulically driven revolving drum, 100 feet of 7/8-inch steel cable, a cargo hook, and a hydraulic load isolator. The cargo hook is designed to support loads of up to 20,000 pounds, although the hydraulic load isolator is restricted to 17,640 pounds. Release of the hook is achieved by an electrical signal transmitted through conductors in the core of the hoist cable. Emergency release is achieved by cable cutters (electrically triggered cartridge cutters). The single winch, which is of the conventional type, is rigidly mounted to the airframe and has a single layer of cable to avoid chafing.

A single-point hoist system has load stability characteristics similar to those of the fixed single-point suspension discussed under SINGLE-POINT SUSPENSION and STABILITY OF SLUNG LOADS, both in the LOAD SUSPENSION SYSTEMS section.

Consideration of single-point hoist systems with a capacity of 40,000 pounds for the heavy-lift helicopter indicates that further development of current techniques is not the answer. Discussion of cable and winch sizes at the beginning of this section indicates that such a system would require the following: a 1½-inch-diameter cable, a 90-inch-diameter winch drum, and a hook weighing approximately 300 pounds. Another extremely important consideration is the effect of cable flexibility which, in the case of a 1½-inch-diameter cable, approaches that of a 1½-inch-diameter lead pipe.

It is of interest to consider the practice used by commercial crane operators. Investigation of the cranes used in the shipbuilding industry (capacity to 100 tons) shows that regardless of capacity, the maximum size cable used is 3/4 inch in diameter. The required weight capacity is achieved by using a reeved cable system. A typical reeved cable system is illustrated in Figure 52. A reeved system requires less straightening load (headache ball) than an equivalent single-cable system. The weight of the lower block contributes to the straightening load and so involves no weight penalty.

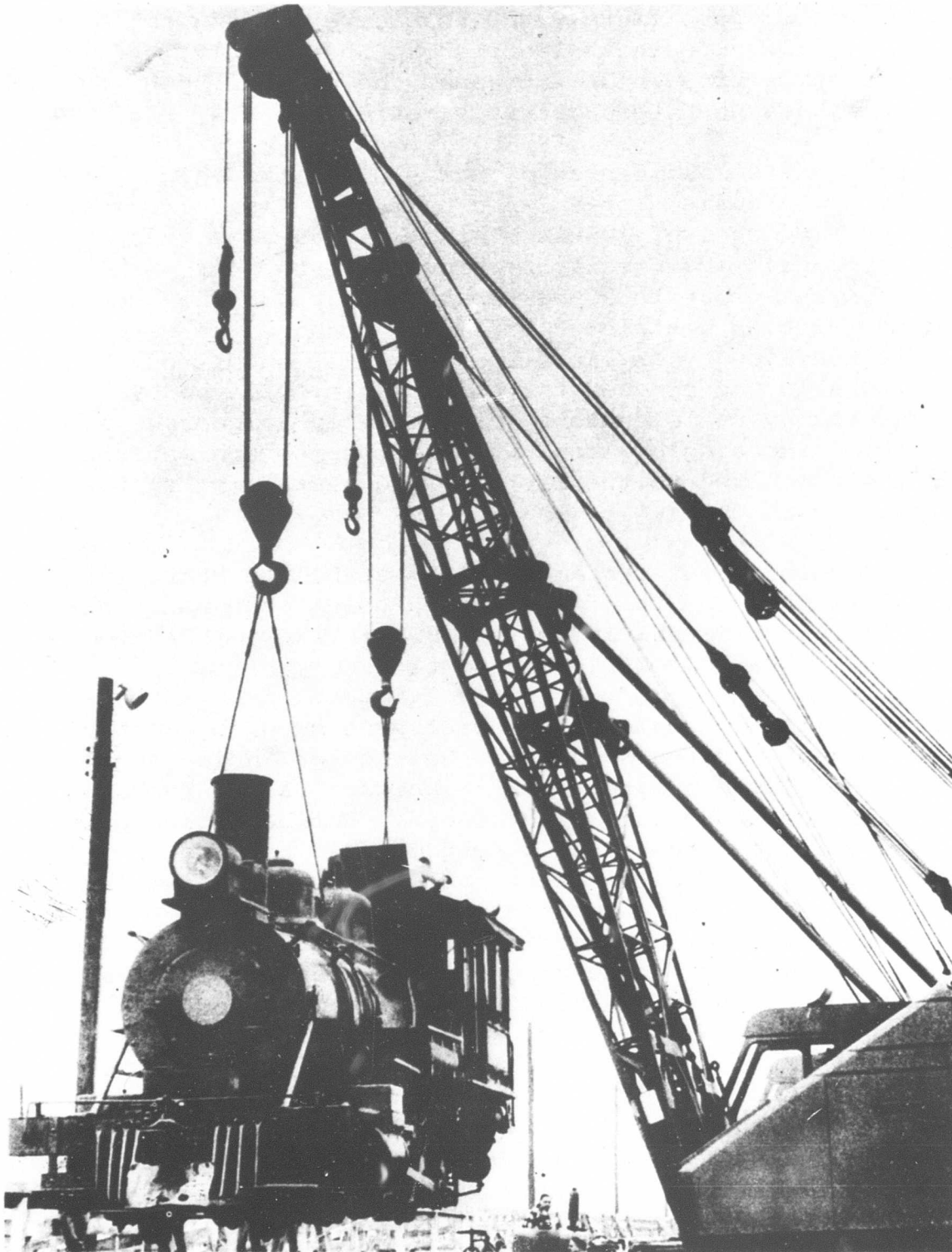


Figure 52 . A Typical Reeved Cable Hoist System

Reeved cable hoist systems have not been used in the past because there have been no problems with cable size. A factor to be considered when using reeved cable systems for single-point suspension is that if the lower block is allowed to rotate, the cables may chafe against each other. Provided a swivel is used and the extension required is not excessive, the inherent restoring moment in the system will inhibit this tendency. To establish feasibility, it is possible to compute the maximum length of a given system that will not wind up on itself. Reeved cable hoist systems are used in pairs and are fastened to a common beam similar to the two-point hoist systems. Winding-up problems are minimized by the restraint provided by the beam.

MULTI-POINT HOIST SYSTEMS

The only airborne multi-point hoist system in existence is the four-point system built for the CH-54A. Multi-point hoist systems are a logical development, based on multi-point suspensions and single-point hoists. The objective is to provide the load stability of the multi-point suspension, while allowing pickup from hover and subsequent hoisting of the load to an optimum position.

Although the CH-54A four-point hoist system has yet to be evaluated, it is apparent that it will be subject to problems similar to those encountered in previous four-point suspension systems; namely, structural redundancy in the legs, and synchronization of the release system.

The structural redundancy could be eliminated by coupling two adjacent legs to a single winch, as shown in Figure 53, but this would require the use of two different types of winches. This would be expensive and would create synchronization difficulties.

Release system synchronization is the overwhelming problem on four-point suspensions. The CH-54A four-point hoist system is not equipped with a pilot-controlled normal release. Normal release must be made by the ground crew, and this is very dangerous. One advantage of a hovering pickup is that out-size loads can be acquired which the aircraft cannot straddle. Obviously, the release must also be made in hover (unless the lines are sufficiently long to allow alongside landing). If the load is only partially released and, because of a gust, the helicopter takes up the load in the hooked legs, it may over-

turn, as described at the beginning of the LOAD SUSPENSION SYSTEMS section. Emergency release of the load on the CH-54A four-point hoist system is accomplished by cable cutters mounted in the winches.

As in the case of multi-point suspension, analysis of various multi-point hoist systems indicates the two-point hoist to be the simplest configuration. An elementary two-point hoist system is shown in Figure 22, and a more versatile system with a connecting beam in Figure 54. Use of a connecting beam bestows several advantages, such as the ability to lift multiple loads. It also allows the hook release mechanism to be mechanically interconnected, which ensures synchronization. Electrical conductors for the hook release mechanism are brought to the center of the beam where they are less likely to become snagged by the cables. Since the cables do not then have to contain conductors, the winch drum may be smaller and lighter.

Aerodynamic stabilization of the load may be achieved by fitting a large vertical stabilizer to the aft end of the beam. The stabilizer would be a bulky item to handle on the ground. Tradeoff studies would determine whether the extra weight and design complexity are offset by a significant increase in allowable airspeed.

When determining the capacity of individual hoist legs in a multi-point suspension, it should be remembered that, in general, the load will not be equally divided. Actual factors to allow for this have not been established, since no experience is available on multi-point suspensions.

HELICOPTER EXTERNAL HOIST SYSTEMS

Winch Design Considerations

Existing helicopter winches, of which the majority are utility rescue types, employ small (1/4-inch) diameter cables. Winding cables of this diameter onto the winch drum creates no bending stress problems. A drum-diameter-to-cable-diameter ratio of 20:1 is used; this is the same cable ratio used in aircraft control system flexible cable runs. When semiflexible cables are used with electrical conductors, higher ratios are used; for example, the Model 64 winch (All-American) has a cable ratio of 59:1 (a 3/10-inch cable has 7000 pounds maximum static capacity).

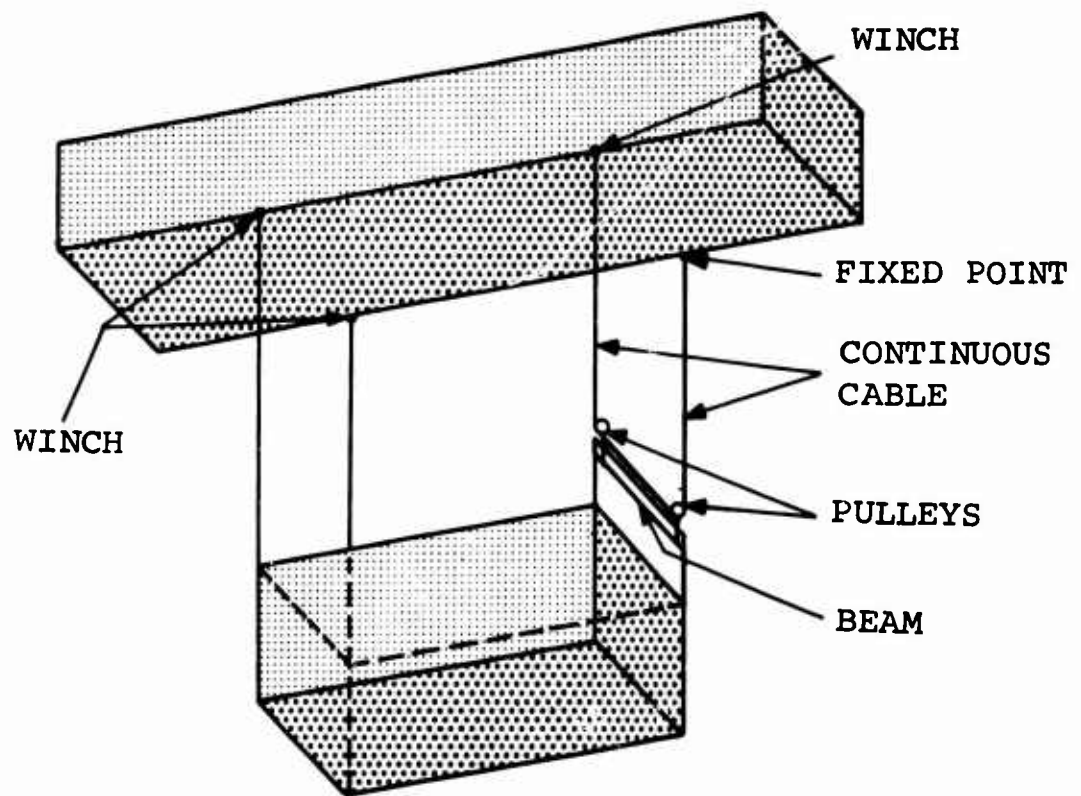


Figure 53. Elimination of Redundancy in Four-Point Hoist System

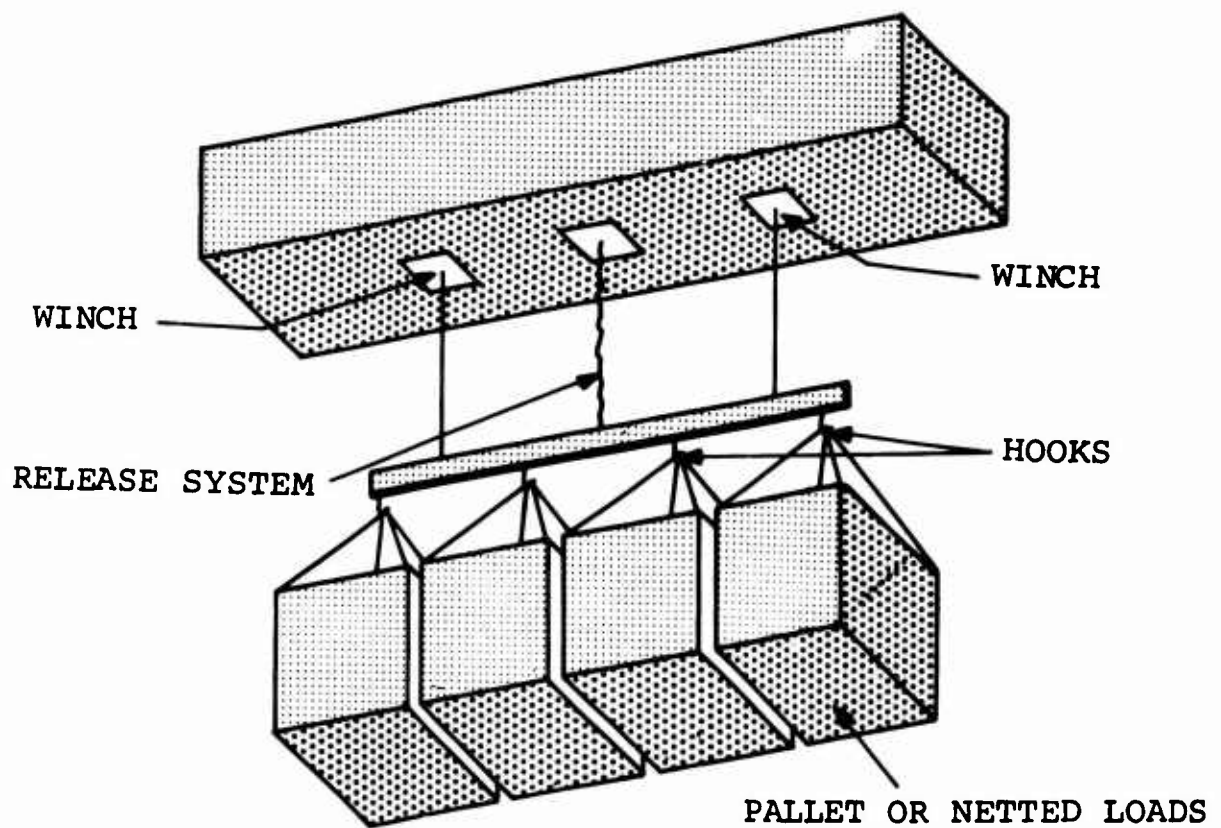


Figure 54. Two-Point Hoist System with Connecting Beam

When larger diameter cables are used, considerations of bending stresses in cables wound on the drum become of great importance (see Figure 46). Even with a ratio of 50:1, bending loads of 5000 pounds are obtained in a 1-inch-diameter cable. If the ratio is reduced to 20:1, the tensile load increases to 13,000 pounds. Tensile loads shown in Figure 46 apply to a 6 x 19 type cable; tensile loads for semiflexible cable would be considerably higher. Cable fatigue is a major problem. The necessity of bending cables on drums and around sheaves contributes to this problem, but this cannot be avoided; reverse bends should, however, be avoided. Large drum-to-cable ratios result in longer cable life.

The capstan or zero-moment-type winch, although it gives an unloaded drum, does introduce more bends into the cable due to winding cable around the capstan pulleys. If drum-to-cable ratios of these pulleys were large, this would not be a major problem. However, a review of existing capstan winches indicates that 20:1 ratios are used.

Rapid accelerations and decelerations of the cable system also increase cable stresses; this, however, is not a major problem in airborne hoist systems.

The following specific recommendations are made for future design of winches for helicopter hoist systems:

1. An emergency cable cutter device controlled from the cockpit is mandatory, to ensure flight safety.
2. A single layer of cable on the drum is desirable unless a capstan-type winch is used; otherwise, chafing of the cable will result from the cable layers fitting into one another. Cable level wind should be mandatory. (A level wind is a device which ensures that the cable is wound on the drum with no overlap.)
3. Cable spring-back after release of load from hover is another consideration. Experience has shown that the cable can jump off pulleys. Good detail design practice should eliminate this problem.
4. Other desirable winch design features would include: cable footage indication, limit switches to control cable overrun, cable tension readout to pilot, and possibly an automatic reel-out feature to reduce

high transient cable loads caused by gusts, etc.

Hoist System (Excluding Winch) Design Considerations

The following recommendations do not include all specific items applicable to the design of airborne hoist equipment. They include only the major items considered to be mandatory as a result of this study.

1. Load release should be under the direct control of the pilot and also the third pilot or load master, if carried.
2. Both electrical and manual methods of hook release should be provided, both controlled from the cockpit.
3. Factors should be established and specified to compensate for centrifugal and drag forces.
4. Electrical conductors should be divorced from the hoist cables.
5. Electrical conductor circuits should be duplicated, each circuit having a separate power source.
6. System base fixation points (i.e., distance between attachment points on helicopter fuselage) should be such that inadvertent release of part of the suspension system does not endanger the safety of the aircraft.
7. Single-point hoist systems should embody a ball-bearing swivel between hook and cable.
8. Variable-speed hoist system control should be mandatory.
9. System load capacity and rate must be specified. Discussions held with personnel of the Army, Marine Corps, and Navy indicate that the relationship between rate and system weight is not fully understood. It must be fully appreciated that, for a given load capacity, doubling the rate means doubling the horsepower required. The subsequent increase in horsepower increases not only the winch weight but the entire hoist system weight. It is appreciated that

to specify the optimum rate is not an easy task. Investigation of commercial hoist systems tends to indicate that the heavier the load, the slower the rate. Little information is available on helicopter hoist systems. The Navy system being developed for vertical replenishment missions used a rate of approximately 60 feet per minute during feasibility trials, and this was considered adequate. To establish the optimum rate for any future hoist system, it is recommended that a test program be initiated.

10. Preflight qualification test requirements should be adequately specified for the entire system. It must be appreciated that today no test facility exists in the United States capable of testing winches already in use on the CH-54A. Such a test facility is urgently required for the qualification of present and projected airborne hoist systems.

SUMMARY RESULTS OF HOIST SYSTEMS ANALYSIS

Summary results of the foregoing analysis of hoist systems are as follows:

1. The development of a two-point hoist system shows promise of resolving some of the problems associated with multi-point hoist systems. Feasibility can be established using existing equipment (winches) which will result in minimum cost. Such a system satisfies load stability requirements; at the same time, its simplicity indicates that all safety-of-flight requirements can be met.
2. Since a single-point lift can be accomplished with a two-point system, further studies should be performed to evolve a system which shows promise of eliminating the need for two separate winch systems. Such philosophy will also keep the cable down to a practical size, particularly in the case of a reeved system.
3. Winch technology has shown no significant change in the last 25 years. Further detail study should be initiated to establish the optimum winch type to perform the specified missions.

4. Some advance in cable technology has resulted in higher strength cable. This has been accomplished by use of swaging and cold drawing techniques which have resulted in stiffer cable; this stiffer cable will require larger drum diameters. Realistic qualification tests should be initiated on new-type high-strength cables.

Discussion with cable manufacturers indicates that the use of woven strip-type cables could possibly result in significant improvement in winch designs. This area requires further study; a test program should be initiated to determine the practicality of such items.

5. No test facility exists in the United States capable of qualifying present and projected airborne winched systems.

LOAD ACQUISITION

LOAD ACQUISITION METHODS

The four basic methods by which helicopters acquire external loads are: (1) hovering pickup, (2) landing alongside the load, (3) taxiing over the load, and (4) moving the load under the aircraft. There is no one optimum method. The best method for an individual case depends upon the type of load and the type of mission.

Both taxiing over the load and moving the load under the aircraft require the helicopter to be equipped with long landing gear in order to straddle the load. Hovering pickup and landing alongside the load do not require special design features. In general, when a load can be straddled and rigidly fixed to the long-gear helicopter, a higher cruise speed is possible. However, load acquisition times are higher, so it would seem that there is no advantage in the long-landing-gear helicopter for short stage lengths. The range at which the tradeoff favors the long-landing-gear helicopter can be determined only by a detailed analysis of particular aircraft designs and loads. It should be noted that comparatively few loads are suitable for rigid restraint without additional special equipment. The various methods of load acquisition are discussed in detail in the following paragraphs. A qualitative comparison is made in Figure 55.

Hovering Pickup Method

There are three ways in which a hovering pickup is used. The load sling may be attached to a cargo hook mounted in the belly of the aircraft, or it may be attached to a cable which is, in turn, attached to the aircraft cargo hook (see Figure 56). The third way is for the aircraft to be fitted with a winch so that the load may be acquired with a convenient cable length and then reeled in to the optimum length for flying qualities (see Figure 57).

The third technique allows acquisition and deployment of loads in locations which are small, and obstructed, or which have a soil load-bearing strength so low as to require a high-flotation, low-motion-resistance landing gear. The pickup and release are fast as long as a ground crew is present to sling the load.

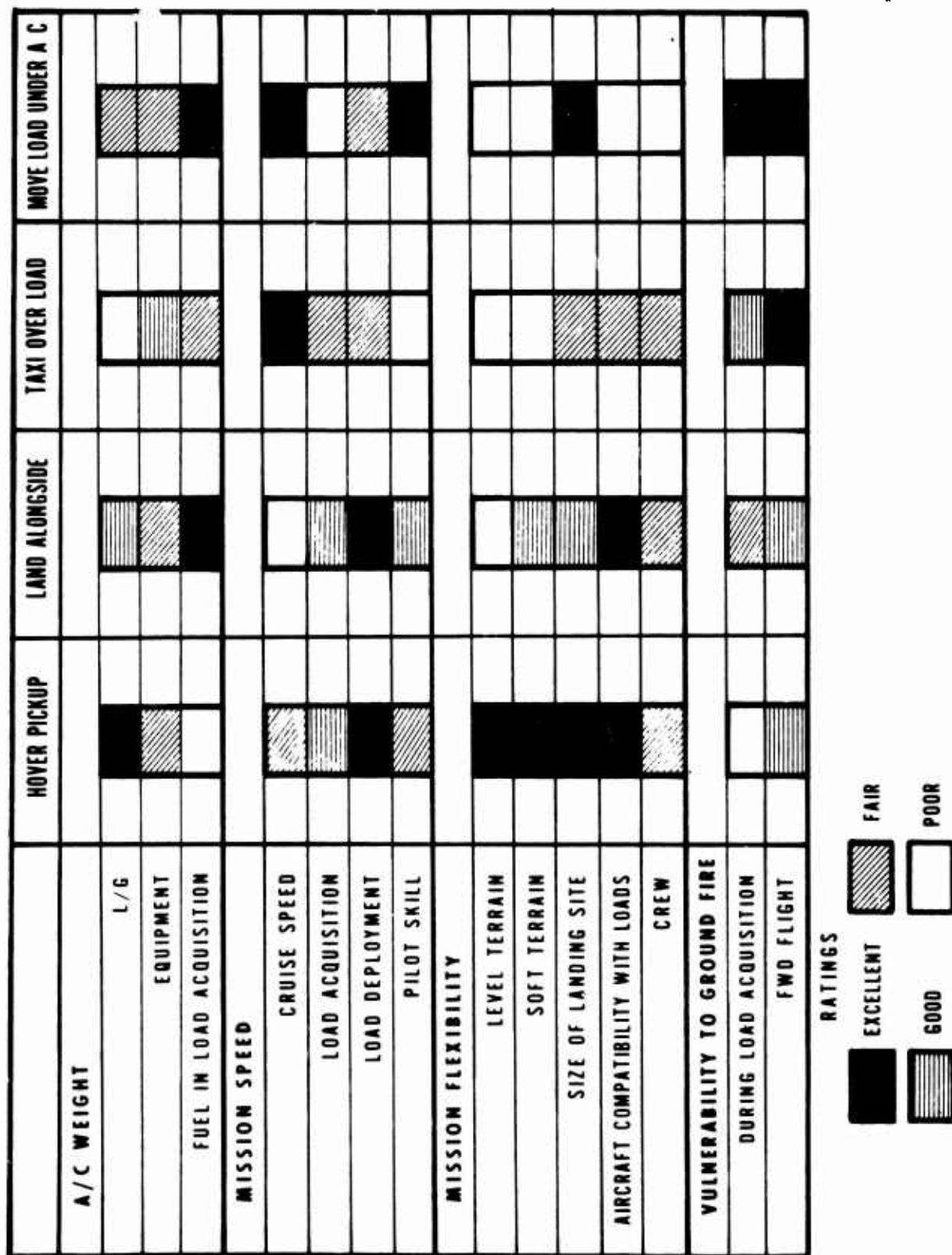


Figure 55. Comparison of Load Acquisition Methods

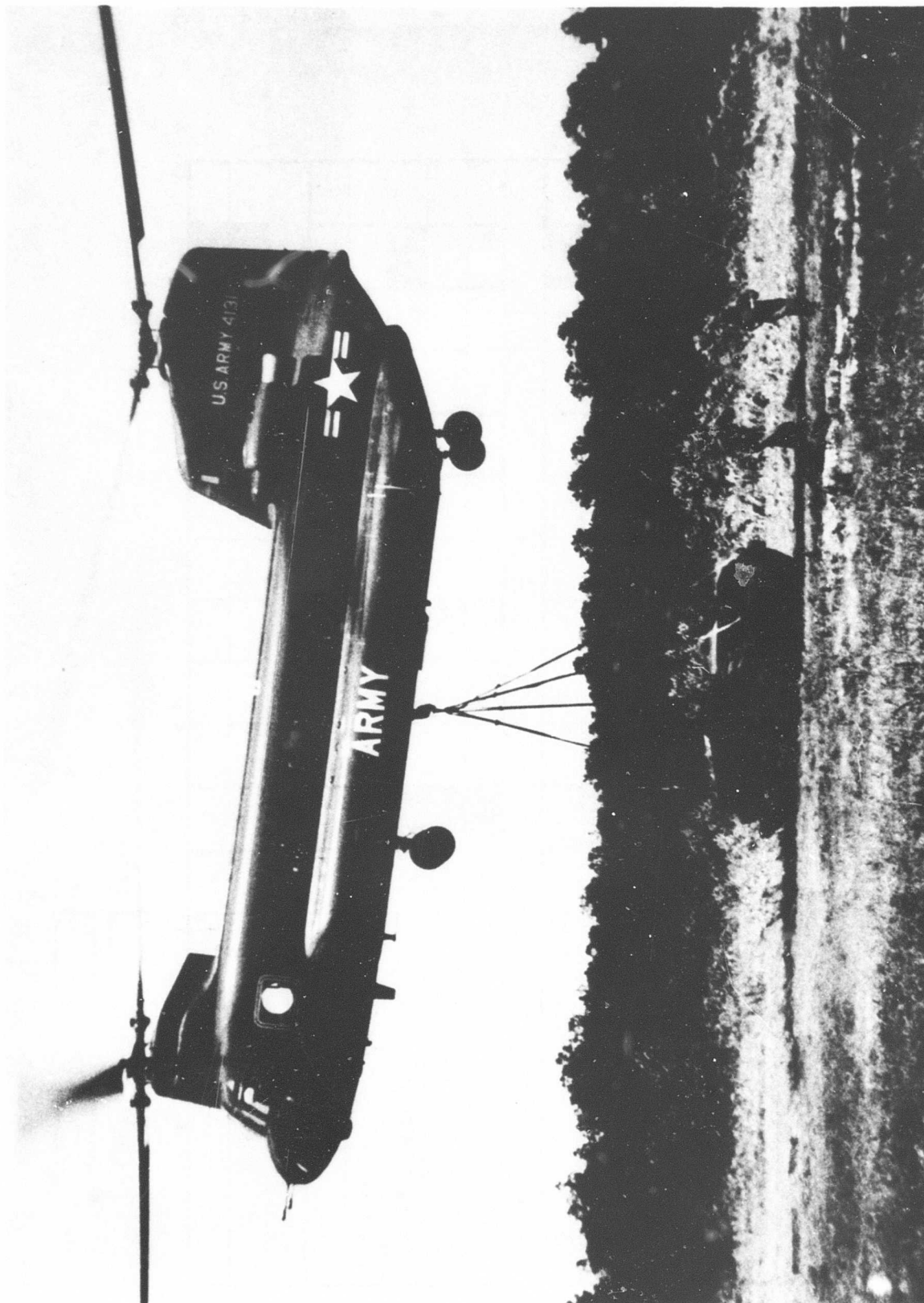


Figure 56. Hovering Pickup with Belly-Mounted Hook



Figure 57. Hovering Pickup with Winch System

With the hovering pickup method, the pilot's visibility depends on the length of cable, if any, and on soil condition (i.e., absence of dust or snow). Pickup with a belly-mounted hook is directed by hand signals from ground personnel and/or rear-facing mirrors. Experience has proved mirrors to be troublesome due to vibration. If pickup must be accomplished over loose dry soil, the dust cloud caused by downwash may limit the pilot's visibility and cause damage to engines from foreign object ingestion. The dust problem may be eliminated by using a long cable, but this makes it difficult for the pilot to maintain altitude and position accurately. The downwash problems are discussed later in this section under Aircraft Ground Mobility Requirements (page 93).

A long cable is sometimes necessitated by the presence of tall trees or other obstructions, but its use in combat areas makes the helicopter more vulnerable to ground fire.

The major disadvantage of hovering load acquisition is the high rate of fuel consumption during hover; in general, the power required, and hence the fuel flow, in hover is at a maximum, particularly when the helicopter is out of ground effect. The magnitude of this penalty is naturally a function of the time taken to acquire the load. If the pickup can be made immediately, the penalty is insignificant; however, if difficulty is encountered, the fuel burn-off can be considerable.

The maximum speed in forward flight is restricted by the aerodynamic stability of the load, since the load is towed at the end of the cable and is not rigidly restrained to the aircraft. These restrictions are discussed for different suspension systems in the LOAD SUSPENSION SYSTEMS section.

Landing Alongside the Load Method

Load acquisition by landing alongside the load has several distinct advantages over the hovering pickup. Hover time is limited to the actual pickup of the load and no time is wasted in hover as a result of sling attachment difficulties. Sling hook-up is not impeded by downwash-induced clouds. The ground crew required to sling the load may be flown in and out by the load-carrying helicopter. The only additional capability required over those necessary for hovering pickup is a high-flotation landing gear for operation in soft soil; low motion resistance is not a necessity. It should, however, be noted

that since the landing gear is required to support only the aircraft minus the load, rather than the full gross weight, the flotation requirements are more easily satisfied.

The cable must be long enough to reach from the parked aircraft to the load; if a winch is not fitted, this length may not be optimum for high-speed flight. Furthermore, when the load is actually lifted, the helicopter will be out of ground effect. In high-altitude conditions, this could result in the amount of lifting capability being limited - compared to a hover pickup with the load attached to the belly hook, which might permit transition to forward flight to be accomplished in ground effect.

As with the hover pickup, the load cannot be rigidly restrained to the aircraft, which, in consequence, may be subject to forward speed limitations.

Taxiing Over the Load Method

For this method, in which the load is acquired by either air or ground taxi over the load, the helicopter must be equipped with a high, wide landing gear, as fitted to the CH-54A and the MIL-10 (see Figure 58). The major advantage of this system is the ability to rigidly restrain the load to the fuselage as discussed in the LONG-LANDING-GEAR HELICOPTER section. This feature enables the aircraft to cruise at higher speeds than if the load were towed at the end of a cable.

Although a large winch is not necessary, some means of lifting the load off the ground is required. This can be either an extendable load suspension or a kneeling landing gear, both of which are fitted on the CH-54A. Another advantage of the high-landing-gear configuration, used in conjunction with a rigidly restrained load system, is that the helicopter can make a running takeoff, enabling it to operate at high gross weight when conditions limit hover performance.

The air taxi approach to the load is limited by pilot skill, visibility, and air turbulence, since the aircraft actually straddles the load and clearance must be maintained. Visibility of the load is poor during load acquisition by a forward-facing pilot; rear-view mirrors or an aft-facing pilot are necessary in order to make a precision approach. If an aft-facing pilot is placed in a chin bubble as in the CH-54A (Figure 59), either the approach must be made in rearward flight



Air Progress Magazine

Figure 58 . Russian MIL-10 Helicopter

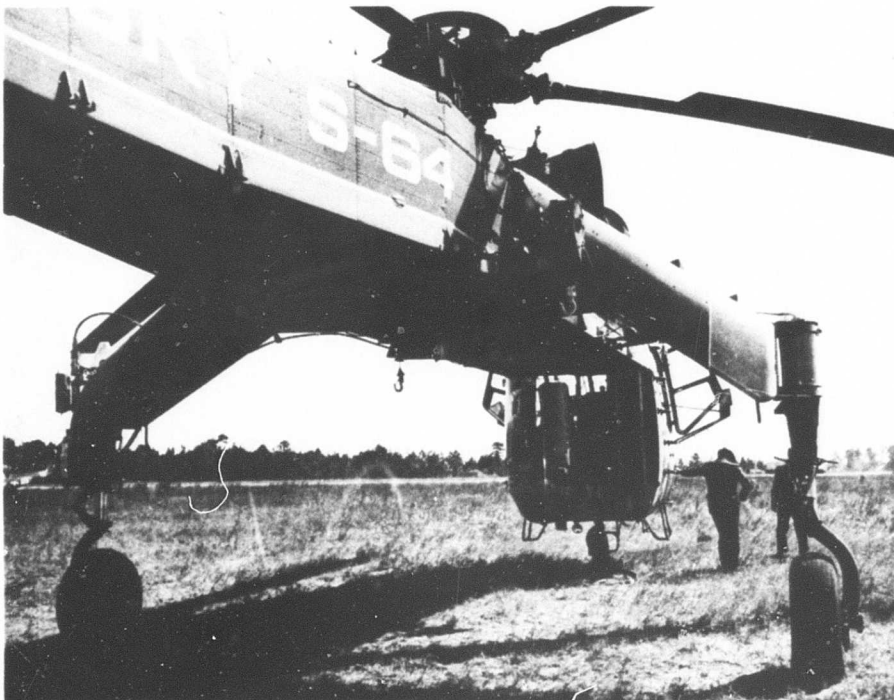


Figure 59. CH-54A Showing Chin Bubble Location of Aft-Facing Pilot

or, in the case of forward flight, sufficient altitude must be maintained for the bubble to clear the load. This latter technique necessitates a transfer of control from forward-facing to aft-facing pilot. Over loose terrain, the rotor downwash will stir up a dust cloud and limit pilot visibility. For these reasons, it is advantageous to make a ground taxi approach to the load. Provided the ground handling characteristics are good and the landing gear affords low motion resistance, a ground taxi approach may be made with precision and low downwash. Soft terrain mobility and downwash effects are discussed in the HELICOPTER GROUND HANDLING section.

Approach to the load depends, of course, on aircraft configuration. In order to taxi forward over the load, it is necessary for the helicopter to be fitted with a quadricycle landing gear, as in the case of the MIL-10. Since this rules out the use of a chin bubble for an aft-facing pilot, rearward vision must be provided by mirrors or television. It is rumored that the MIL-10 helicopter uses closed-circuit television for monitoring the load during acquisition. Vertol studies, however, have indicated that the picture quality is limited for such a system and that the pilot has no depth perception. Recent changes in the state of the art may have changed this situation. A further possibility is to put a forward-facing pilot in an aft-mounted bubble; this, however, involves a communication problem between pilots.

If the helicopter has a tricycle gear, or a nose bubble configuration such as that used on the CH-54A, it is necessary to taxi backwards over the load. The capability to taxi backwards at low collective pitch settings is largely dependent on the rotor configuration. This is discussed under HELICOPTER GROUND HANDLING later in this section.

Moving the Load Under the Helicopter Method

The aircraft requirements for this mode of load acquisition are similar to those previously discussed for taxiing over the load, with the exception that low motion resistance and good ground handling are not required. Pilot visibility is not a problem and no special flying skill is required. See Figure 60.

In addition, either the aircraft must be equipped with a winch in order to pull the load into position (the load being either fitted with wheels and a means of steering or placed on a dolly), or the load must be handled by ground support equipment

such as forklift trucks. The ground support equipment must be capable of operation in unprepared terrain. One objection that the Army 478th Flying Crane Company, which operates the CH-53, has with regard to its equipment is the lack of mobility under these conditions.

Advantages of this method over the taxi approach are minimum hover and taxi time and, thus, lower fuel consumption; also, since the load can be handled with precision, the landing gear clearances may be reduced. Since the aircraft is equipped with long landing gear, it has the advantage of running takeoff capability. In addition, if the load is rigidly restrained, high airspeeds are possible. Vulnerability to ground fire is low because little or no hover time is required and the rotor may be stopped during loading.

Load acquisition time is high, since the load has to be moved and then positioned accurately before tiedown (see Figure 60). In the transportation of some loads, such as vehicles, the use of a ground-level platform attached to the helicopter landing gear may reduce loading time. These systems are discussed under EXTERNAL LOAD PLATFORMS on page 119.



Verti-Flyte Magazine

Figure 60. Load Being Moved Under CH-54A

HELICOPTER GROUND HANDLING

The mission flexibility of crane-type helicopters is strongly dependent on their ground mobility and flotation capability. This is particularly true of long-landing-gear helicopters which are required to taxi over the load in soft terrain. Helicopters which acquire a load from hover do not, in general, require low motion resistance in soft soil, but good flotation is a necessity.

High-flotation and low-motion-resistance landing gear generally involves a weight penalty to the aircraft. The increased capability of the system must be set off against this penalty in order to determine whether the tradeoff is effective for the particular mission. For this reason, general conclusions cannot be drawn on the optimum flotation and motion resistance capability required of a crane-type helicopter. The actual requirements are subject to a detail study which is beyond the scope of this contract.

The following discussion describes the flotation and motion resistance performance of the CH-47A and CH-54A and gives a preliminary parametric analysis of a heavy-lift helicopter landing gear.

Landing Gear Flotation Requirements

Landing gear flotation requirements are specified to make the aircraft compatible with its intended environment. In the case of the heavy-lift helicopter, it is necessary to operate from all prepared and most unprepared landing areas. This requirement may be broken into three separate items:

1. The aircraft must not damage Zone of Interior airfields.
2. Damage to Theater of Operations landing areas must be such as to allow sufficient operation between resurfacing.
3. The aircraft must be able to lift off safely from specified soft soils.

Item 1 is readily satisfied by adhering to the allowable wheel loads, etc., as specified in the Handbook of Instructions for Aircraft Design (HIAD).

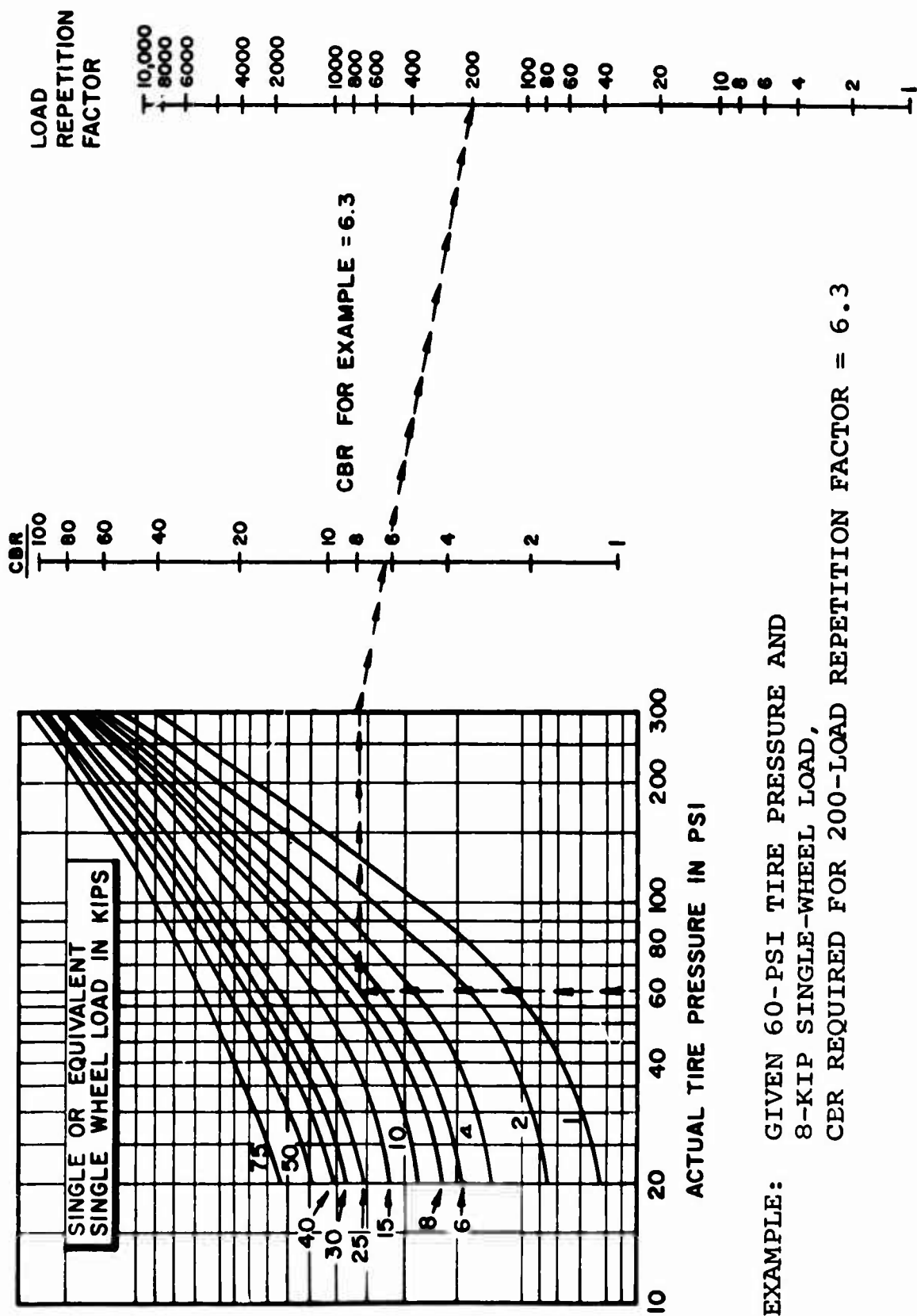
Item 2 is handled in the same way by using the California Bearing Ratio (CBR) nomograph (Figure 61), except that it is necessary to define the number of coverages required between resurfacing operations. This latter information is obtained from an operations analysis of tactical situations.

Item 3, lift-off capability in soft soils, is a very difficult thing to define. In order to understand just what is required, it is necessary to consider the behavior of a helicopter in such a situation. In the first instance, it is important to maintain a substantially level attitude on the ground; the actual tolerance is dependent on helicopter configuration.

Figure 62 illustrates the case of an articulated-rotor helicopter, single or tandem, with one gear submerged in soft terrain, resulting in a roll angle ϕ . In order to take off, the pilot must first put on full lateral stick, resulting in the tip path plane being tilted an amount, β , towards the horizontal. It is then necessary to pull collective pitch and gradually apply thrust. In the case of the hingeless rotor (Figure 63), when lateral stick is applied, the tip path plane tilts a small amount. If the roll angle, ϕ , is large, it is possible for the helicopter to overturn. The criterion for overturning is

$$\phi \leq \beta \left(\frac{u}{w} + 1 \right) + \frac{M_R}{T \cdot w} . \quad (12)$$

For a teetering rotor, the hub moment, M_R , is zero; therefore, typically, the overturning angle is 2β , or twice the maximum lateral tip path tilt. Articulated-rotor helicopters with a flap hinge offset exhibit a hub moment which is approximately proportional to the hinge offset. The hub moment for articulated-rotor helicopters is typically equal to that due to tip path tilt. Hingeless-rotor helicopters are limited in the amount of tip path tilt, but make up for this with increased hub moment. Practical hingeless-rotor helicopters exhibit a lateral control power only slightly in excess of articulated-rotor helicopters. Figure 63 shows a plot of lateral righting moment as a function of hinge offset. Note that a condition for overturning is that a wheel must be prevented from moving laterally; it is not necessary for it to be stuck.



EXAMPLE: GIVEN 60-PSI TIRE PRESSURE AND
8-KIP SINGLE-WHEEL LOAD,
CBR REQUIRED FOR 200-LOAD REPETITION FACTOR = 6.3

Figure 61. California Bearing Ratio Required for Operation of Aircraft on Unsurfaced Soils

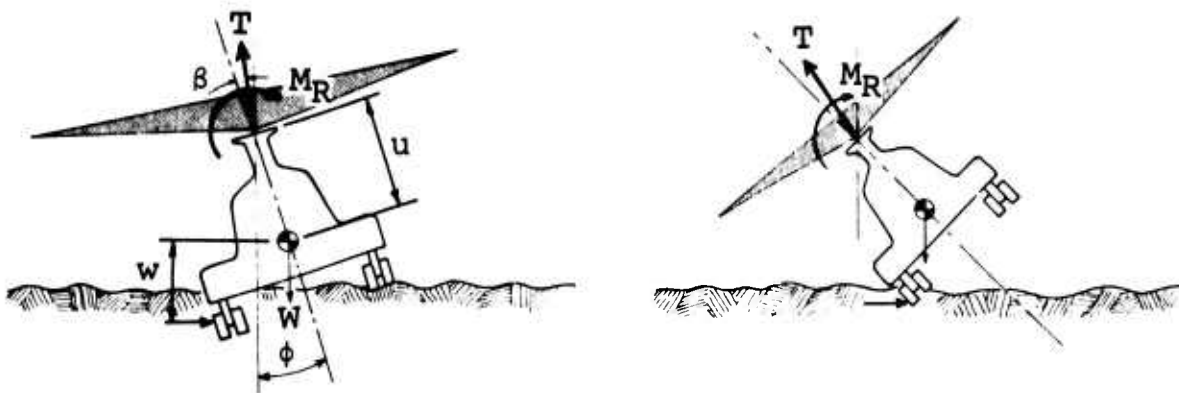


Figure 62. Takeoff of a Helicopter with One Landing Gear Immersed in Soft Soil

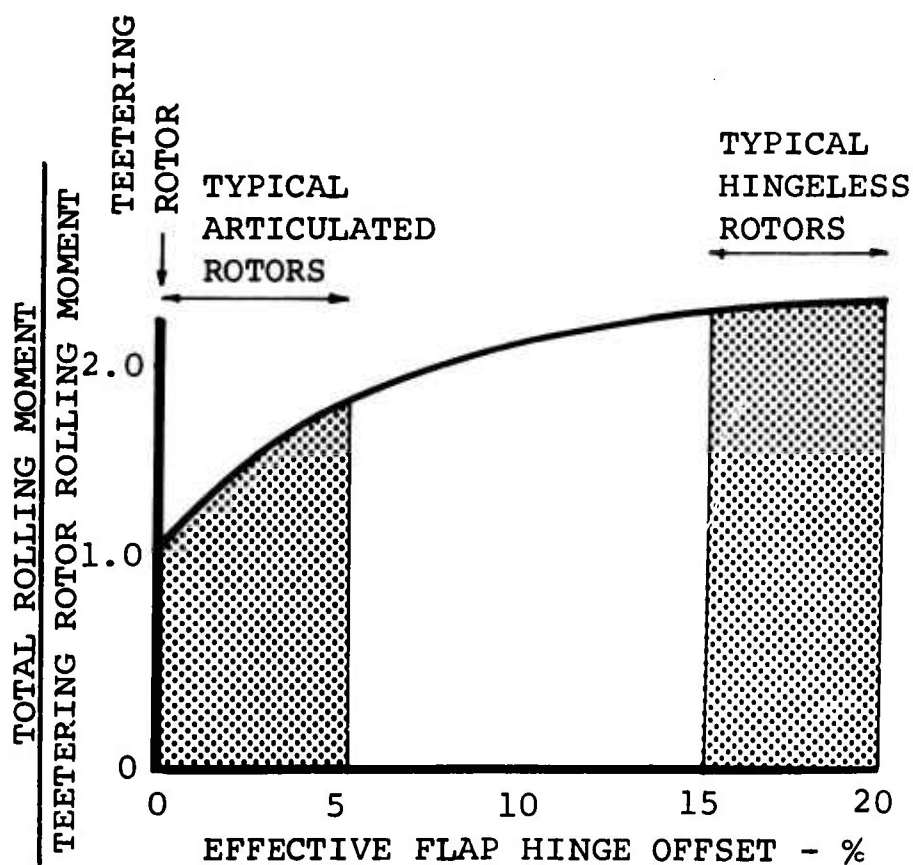


Figure 63. Comparison of Approximate Lateral Control Power for Various Typical Helicopter Configurations

If a helicopter lands on soft terrain and all the landing gears sink deeply, the problem of lifting off is not so much dependent on the aircraft configuration as on pilot technique. The approach generally taken is to apply a rotor thrust of less than gross weight and to loosen each gear, in turn, by applying cyclic stick. The difficulty is in judging the correct amount of thrust since, if it is too low, the cyclic stick motion will result in the gear's squirming even deeper into the mud; whereas if too much is applied, one gear may let go and the aircraft can overturn. The problem of a running takeoff will be considered later in this section under the heading Aircraft-Ground Mobility Requirements (page 93).

It is necessary, therefore, to design a landing gear which will not become deeply immersed in the soil that may reasonably be expected to exist in a given operational theater. This requirement naturally shifts the problem into the area of defining the spectrum of soil strengths. There are several methods of defining soil strength. Three methods which are used by various departments of the Army are:

1. California Bearing Ratio (CBR) - Developed originally by the California Department of Highways, it is usually used in road and runway construction work.
2. Cone Index - This is a description of soil strength, determined by measuring the load required to push a pointed stick (cone penetrometer) into the soil. The index is used by the Corps of Engineers, Waterways Experiment Station (WES) in describing trafficability of Army vehicles. It is also the way in which CBR is determined in the field, using a correlation factor.
3. Soil Modulus - This method attributed to Bernstine, Reference 10, is commonly used in civil engineering in the analysis of foundation sinkage. The soil modulus concept was extended by M. G. Bekker and the Land Locomotion Laboratory (LLL) of the Army Tank-Automotive Center (ATAC) to include the effect of footprint width and change of strength with depth.

Based on these parameters, Bekker has developed analytical techniques to predict the sinkage and motion resistance of all manner of gear types, including pneumatic tires, rigid wheels, skis, and tracks.

An approximate comparison of the three methods of defining soil strength is shown in Figure 64. Both WES and LLL have performed soil strength surveys in the United States and abroad; it is, therefore, advantageous to use these data in assembling a soil strength spectrum. In the design of military vehicles, LLL uses as a lower design limit a soil strength of between $k = 3$ and $k = 7$. This band is called the "Frequently Encountered Critical Soils". It may be seen from Figure 64 that this corresponds to a soil in which a foot soldier will sink to his boot uppers.

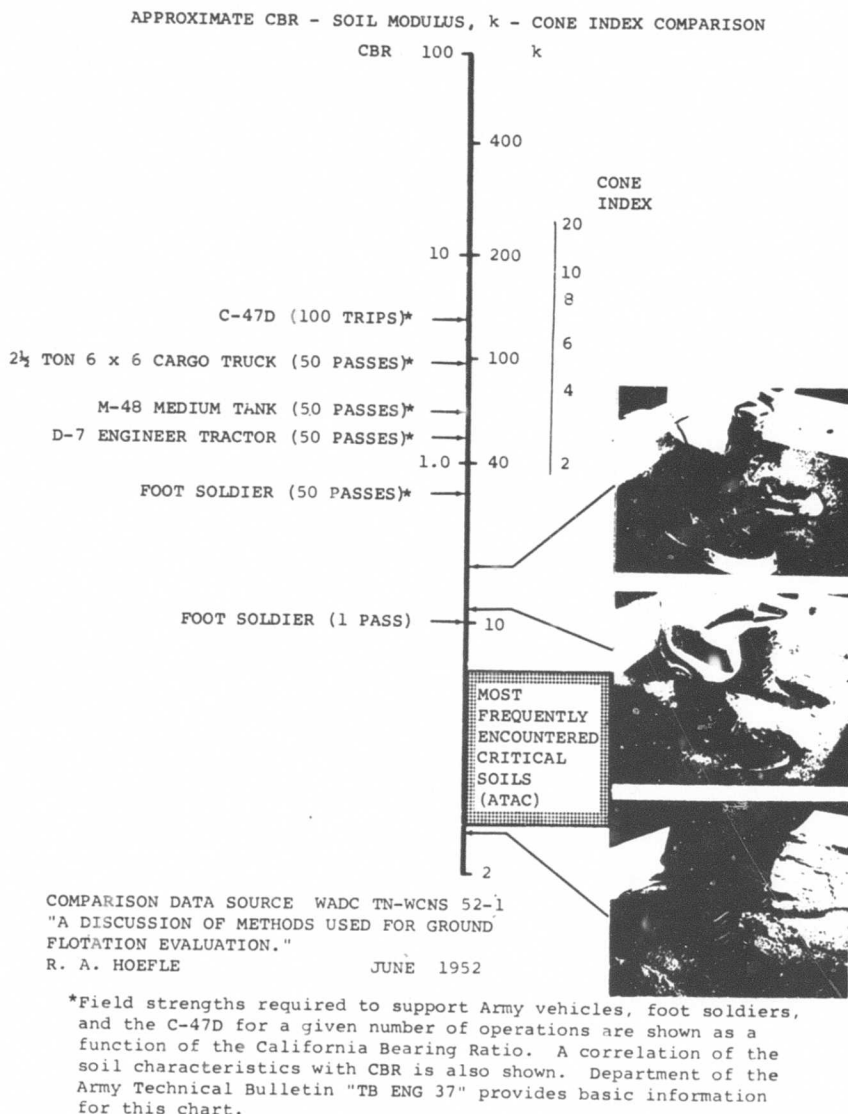


Figure 64. Soil Parameter Comparison

Based on Bekker's studies, Vertol Division of Boeing has developed a method for analyzing high-flotation landing gear types. In addition, Vertol Division has recently completed a separate development study of high-flotation landing gear types under a Navy contract. This work (Reference 5), entitled "CH-46A Unprepared Terrain Mobility Study", is used to compute the sinkage and motion resistance of different gear types. Figures 65 and 66 are plots of wheel sinkage computed for the CH-47A and CH-54A. It is interesting to note that, for very soft soils, the concept of low inflation pressure and large footprint area is difficult to apply in a practical landing gear. In soft soil, a landing gear tire behaves like a rigid wheel and no footprint is formed. When this condition occurs, an inflation pressure of 50 or 500 psi would not affect sinkage and motion resistance, which are controlled by tire size.

Aircraft Ground Mobility Requirements

The basic question to be answered when defining mobility criteria for a helicopter is: why have the capability at all? The major reasons are:

1. For a running takeoff at high gross weight or high density-altitude.
2. For ground taxiing at airfield.
3. For ground taxiing to acquire a load, under any soil condition.
4. For autorotative landing with forward speed.
5. To permit towing for maintenance, etc.

A helicopter equipped with a wheel- or track-type landing gear automatically satisfies requirements 1, 4, and 5 above, when operating from prepared sites. However, in considering ground-taxiing, running-landing, and takeoff requirements in soft soil, it is necessary to discuss motion resistance.

Let us first examine how a helicopter generates the thrust required for taxiing. Figure 67 illustrates a typical helicopter in the ground taxi condition. It can be seen that the horizontal thrust required to taxi the aircraft is dependent on total rotor thrust and on tilt of rotor tip path plane with respect to the ground.

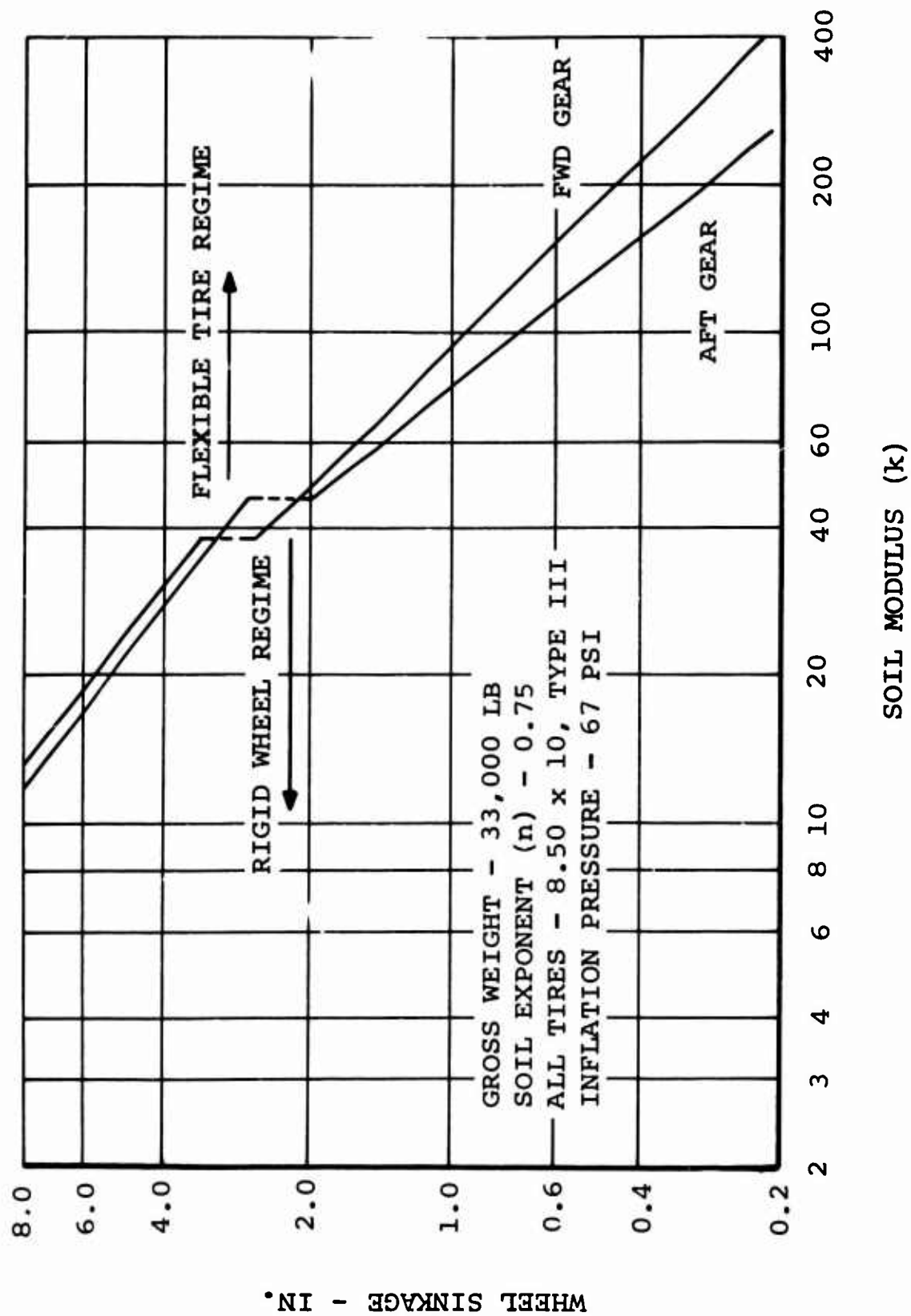


Figure 65. CH-47A Tire Sinkage

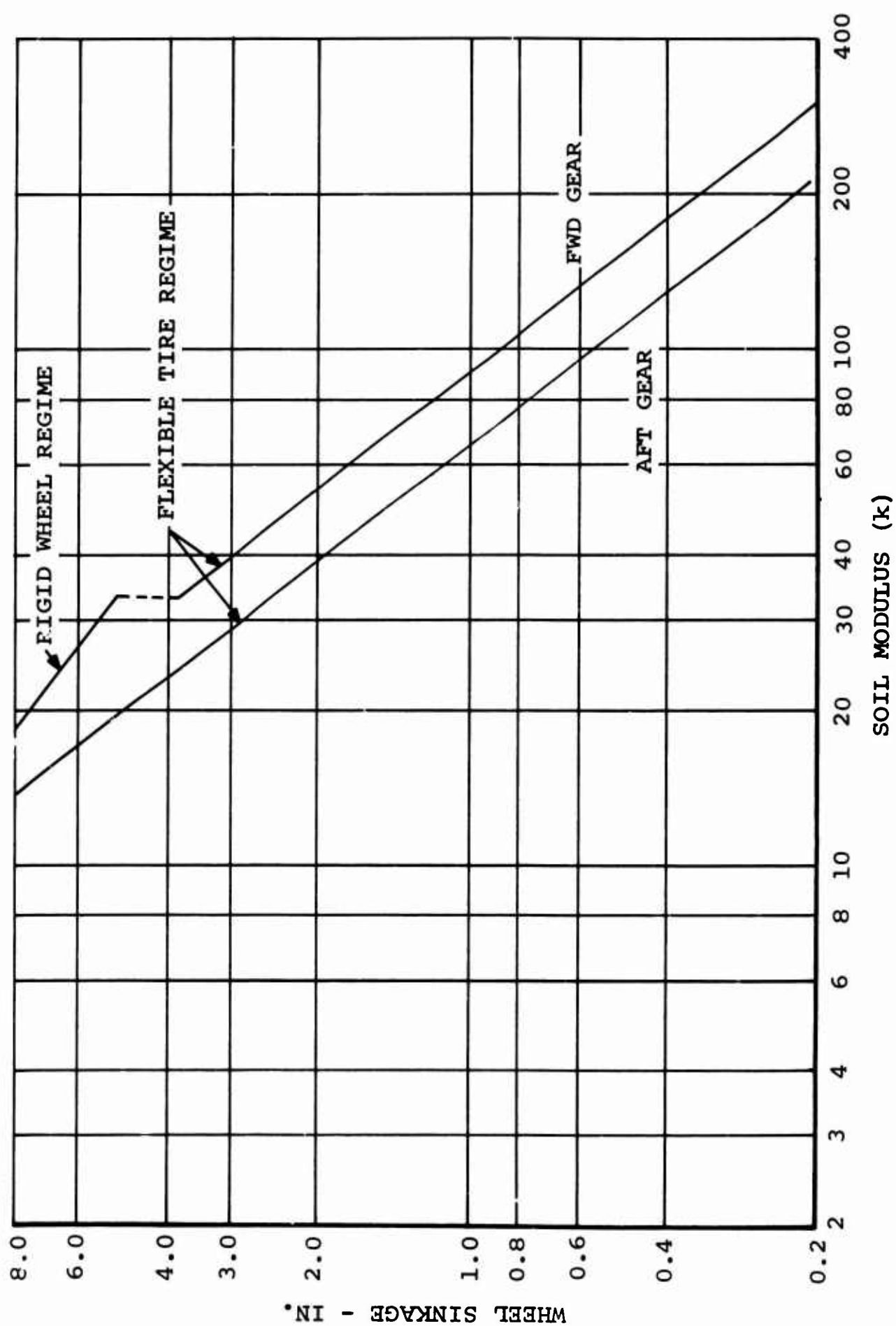


Figure 66. CH-54A Tire Sinkage

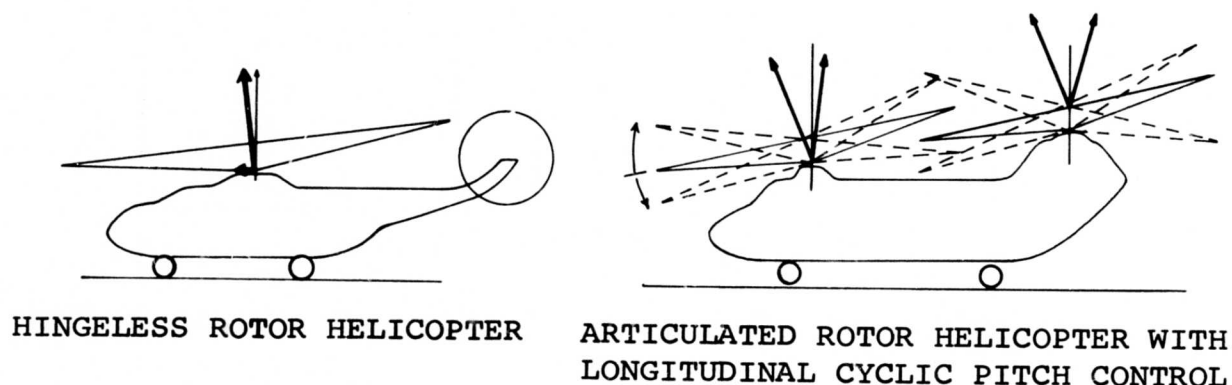


Figure 67. Rigid and Articulated Rotor Helicopters in Forward Ground Taxi Condition

In the case of an articulated rotor without longitudinal cyclic pitch control, as used in tandem-rotor helicopters, the tip path tilt is fixed -- usually from high-speed flight considerations. The horizontal thrust is then a fixed percentage of the total thrust. Therefore, for the aircraft to move backwards, it is necessary to lift the nose off the ground and tilt the whole aircraft backwards.

An articulated rotor with longitudinal cyclic pitch control or (to a more limited extent) a hingeless rotor can be tilted in the fore and aft plane. Consequently, within the limits of the pitch control, a greater horizontal force may be generated for a given total rotor thrust.

Yaw control, or turning force, is generated in different ways for single- and tandem-rotor helicopters. The single-rotor aircraft is steered with the antitorque, or tail, rotor. It should be noted that no main rotor thrust is required when turning. The tandem-rotor helicopter is guided by differential lateral cyclic pitch and rotor thrust, which produce a yawing movement, as shown in Figure 68.

It is sometimes argued that ground mobility in soft soil is an unnecessary requirement and that the helicopter may hover or air taxi under these conditions. Unfortunately, it is not always possible to air taxi for reasons stated in the following paragraphs.

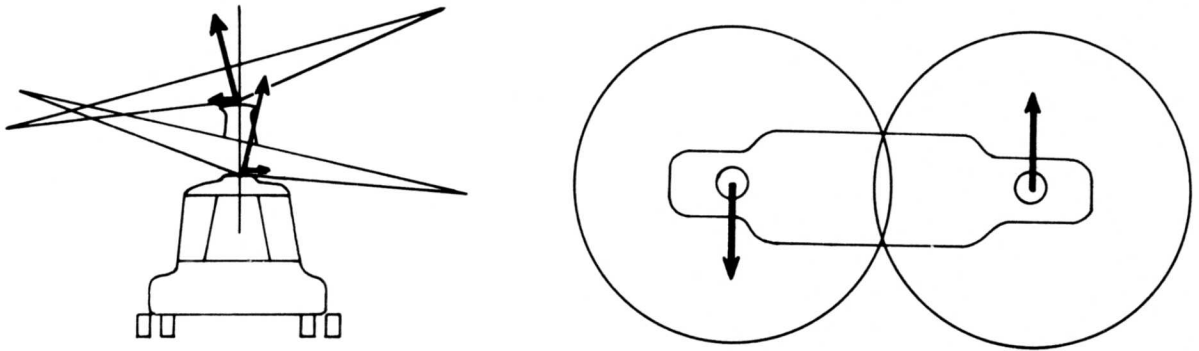


Figure 68. Turning Forces on a Tandem-Rotor Helicopter

In order to hover, it is axiomatic that the rotor produces downwash. This varies in intensity according to the rotor disc loading (rotor thrust divided by the rotor disc area). When flying over loose soft soil or snow, a cloud of dust and debris is stirred up, limiting pilot visibility and causing the engines to ingest foreign objects (stones and dirt). Under these conditions, it is common practice to make a run-on landing and takeoff in order to stay ahead of the cloud.

As explained above, it is necessary to apply a percentage of the rotor thrust in order to ground taxi, and this also causes dust clouds. Since the dust problem and the propulsive force are both a function of rotor thrust, reduction of motion resistance lessens the dust problem.

Another important reason for ground taxiing in soft terrain is the acquisition of external loads by crane-type aircraft. Once again it can be argued that an air taxi approach is the best technique; however, in turbulent air the precision with which a pilot can hold a course is limited. This necessitates greater clearances between the load and the landing gear, with a resultant weight increase. A ground taxi approach to a load can be made with greater precision than an air taxi, provided the ground handling of the aircraft is good. Qualities required to ensure good ground handling in soft soil are low motion resistance and ease of turning. The maneuvers should be smooth with low breakout loads. If the gear has small wheels and sinks deeply when the aircraft is stationary, a large breakout force is required. To generate a large horizontal force, a large rotor thrust must be applied, which

results in a surge, since the gear is now running along the surface. Correction of this sudden motion (surge) by reducing the rotor thrust causes the gear to sink and bog down once more.

One approach to solving the problem of ground handling, while minimizing the landing gear weight, is to power the wheels. This concept is not new, but the projected heavy-lift helicopter may be the first aircraft on which a wheel-powered landing gear may be practical from a cost-effectiveness standpoint. Further study of this question is recommended.

It is apparent from the above text that careful attention must be paid to the motion resistance of the heavy-lift helicopter. As stated previously, specification of a fixed CBR will not define the motion resistance of the vehicle. Parametric studies of tires suitable for the heavy-lift helicopter indicate that substantial changes in motion resistance may be achieved by altering the number of tires. Plots of nondimensional motion resistance as a function of 1-pass

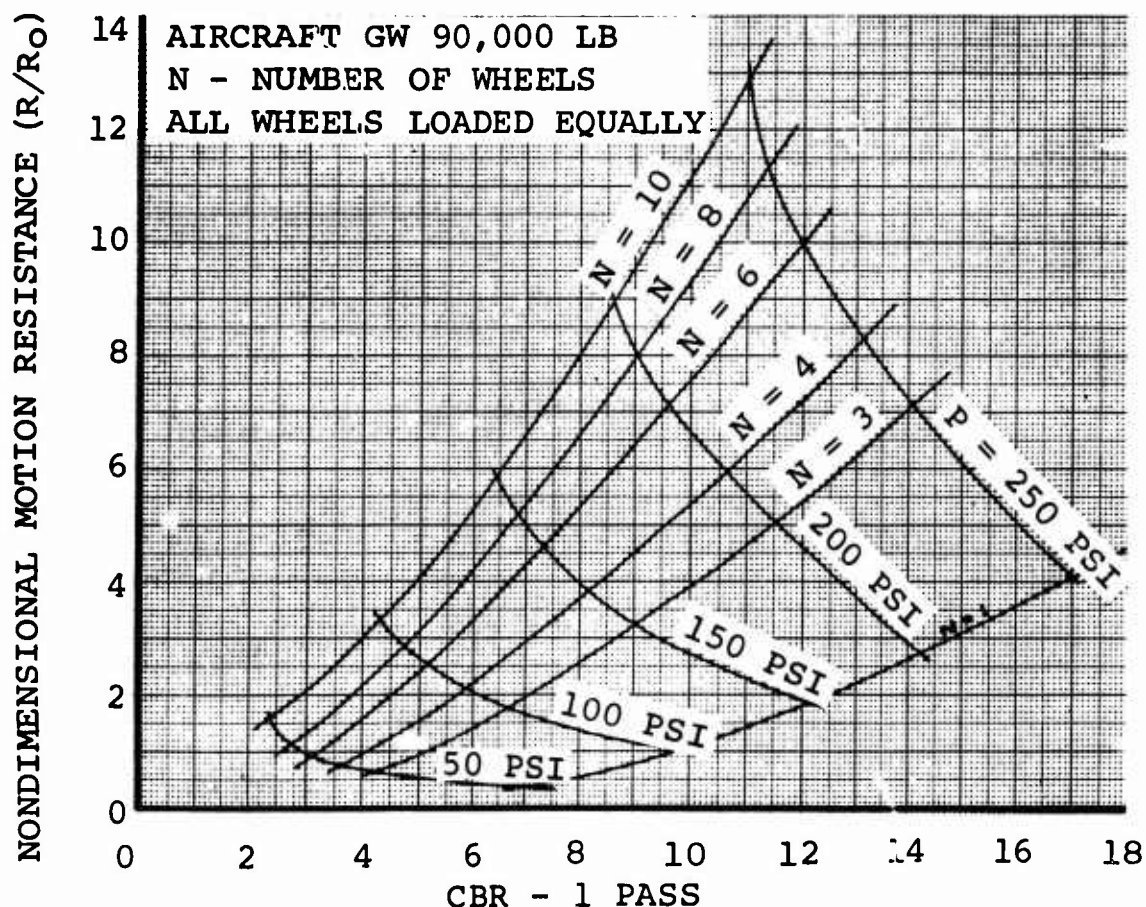


Figure 69. Motion Resistance of Various Heavy-Lift Helicopter Wheel-Type Landing Gear Configurations

CBR for various combinations of tires and pressures are shown in Figure 69. Corresponding approximate tire sizes are shown in Figure 70. It should be noted that in computing the CBR for multi-wheel landing gear, each wheel was considered to be isolated from the other wheels. The equivalent single-wheel load was considered to be equal to the single-wheel load; generally, this is not practical. Actual multi-wheel configurations will, therefore, require larger tires at lower pressures than shown.

Figure 71 is a plot of nondimensional motion resistance as a function of tire diameter-to-width ratio and number of tires. Each tire is at a constant inflation pressure and is rated at 35-percent deflection. It may be seen that a reduction in motion resistance of approximately 17 percent is possible by using tires with the highest diameter-to-width ratio, although it may be found that the high-aspect-ratio tires are disproportionately heavy.

A curve showing the motion resistance of the CH-47A and CH-54A in the soft soil is given in Figure 73.

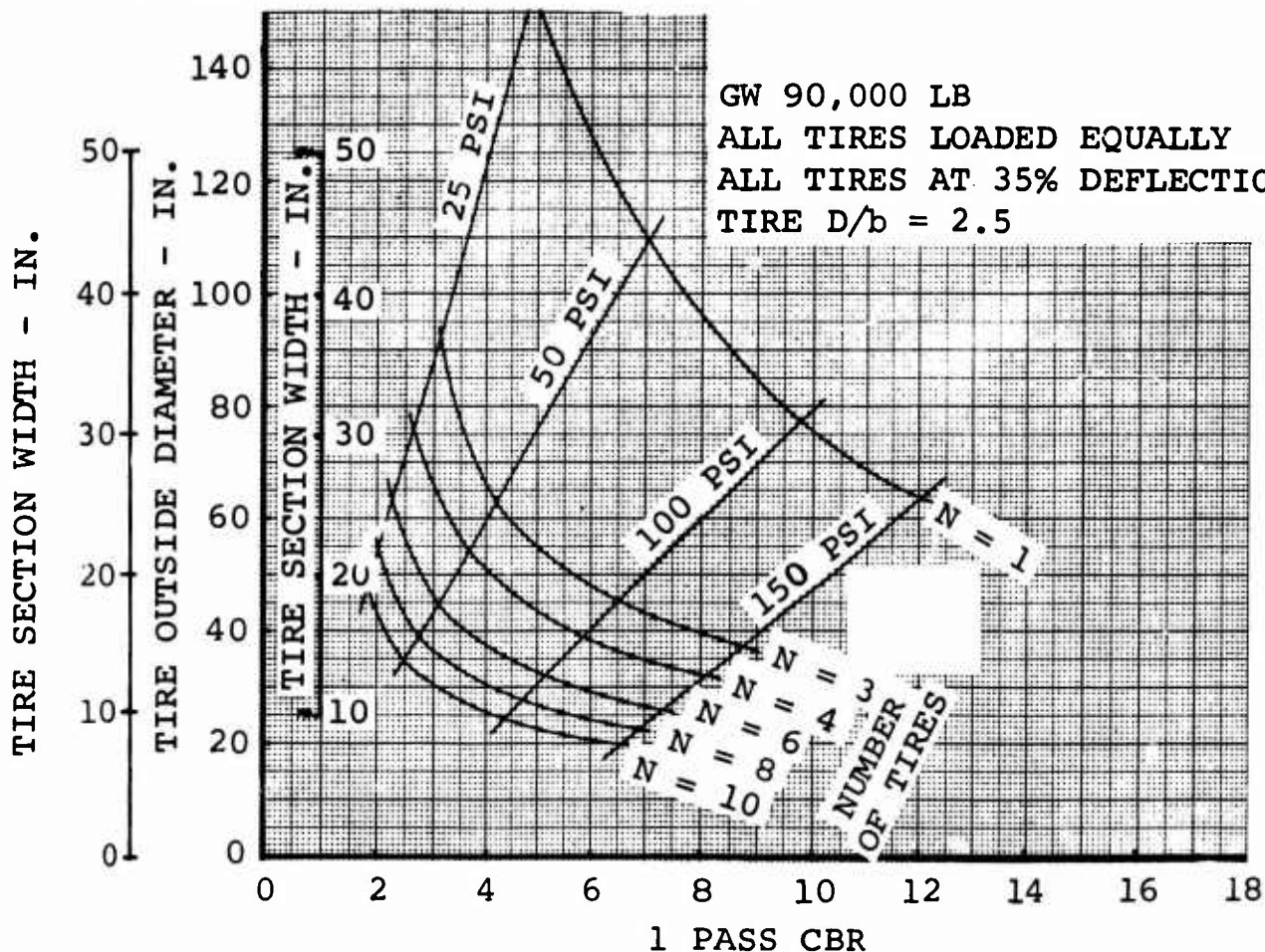


Figure 70. Heavy Lift Helicopter Tire Size

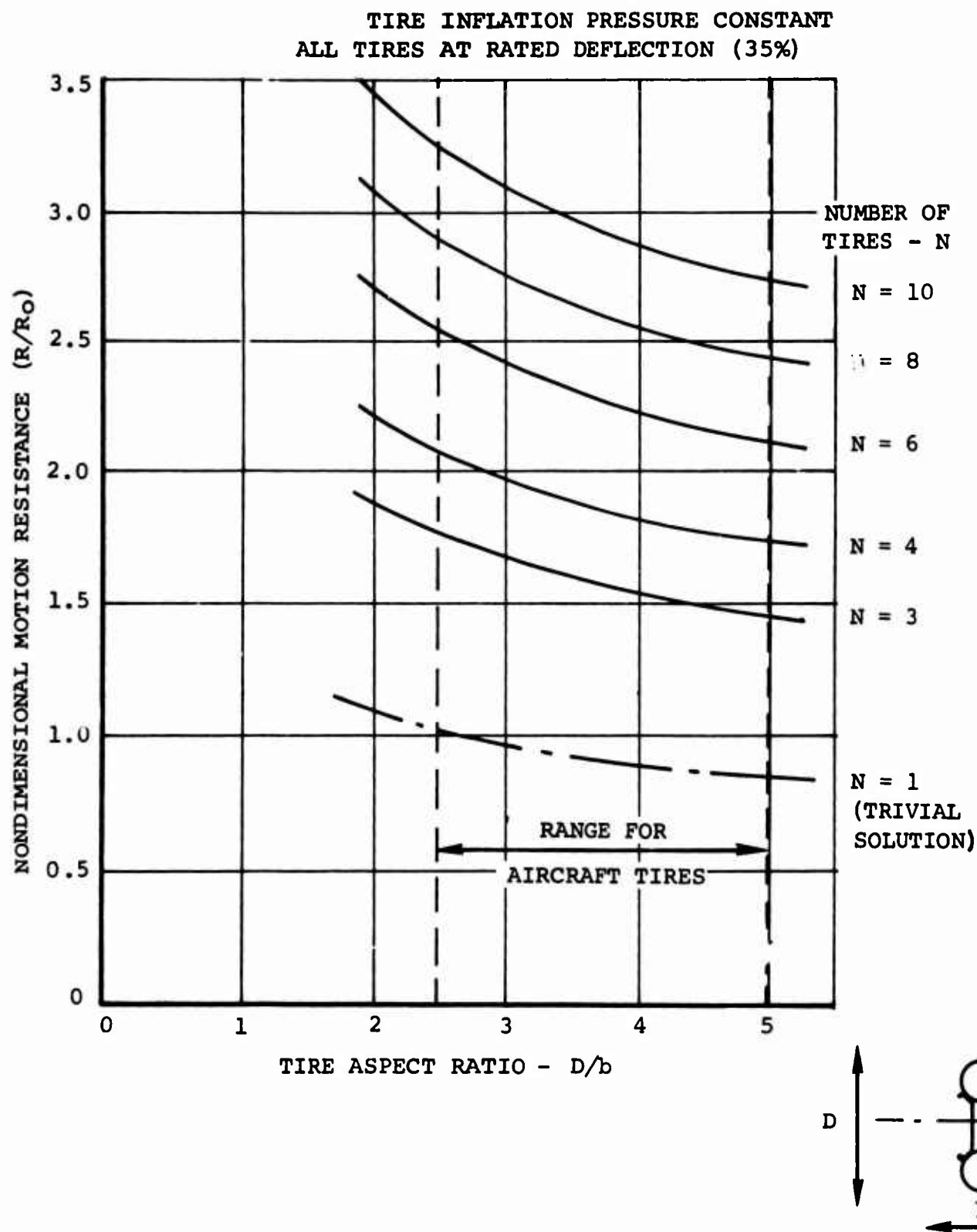


Figure 71. Effect of Aspect Ratio and Number of Tires on Aircraft Motion Resistance

The above parametric study applies only to tires operating in soil which is sufficiently strong to bear a footprint. In very soft soils the tire behaves like a rigid wheel, and tire sinkage and motion resistance depend only on tire diameter and width. The point at which transition occurs from flexible tire to rigid wheel regimes depends on both tire and inflation pressure. Figure 72 shows the effect of inflation pressure on the motion resistance of the CH-46A. It can be seen from this plot that the well-known trick of reducing the inflation pressure of a vehicle stuck in soft terrain is very effective, but only if the pressure is reduced sufficiently to enable the tire to form a footprint.

In practice, it would be difficult to provide a very low-pressure tire in order to operate in the flexible tire regime. Therefore, it is necessary to consider performance in the rigid wheel regime when operating in very soft soils. If the vehicle is equipped with few large-diameter tires, the very-soft-soil flotation may be adequate in the rigid wheel regime, as the sinkage may be a relatively small percentage of the wheel diameter. On the other hand, the same vehicle with many smaller tires may find the tires buried, under the same conditions. Refer to Figure 73.

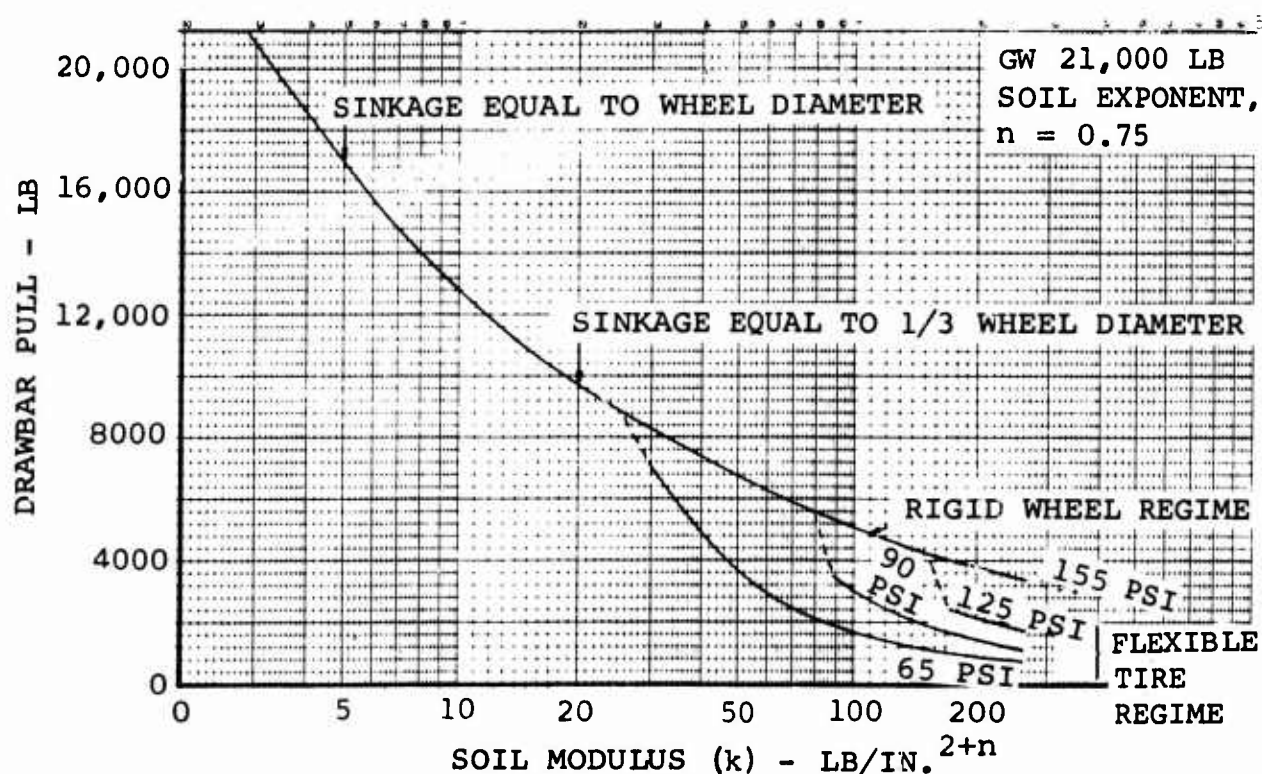


Figure 72. Effect of Tire Pressure on CH-46A Motion Resistance

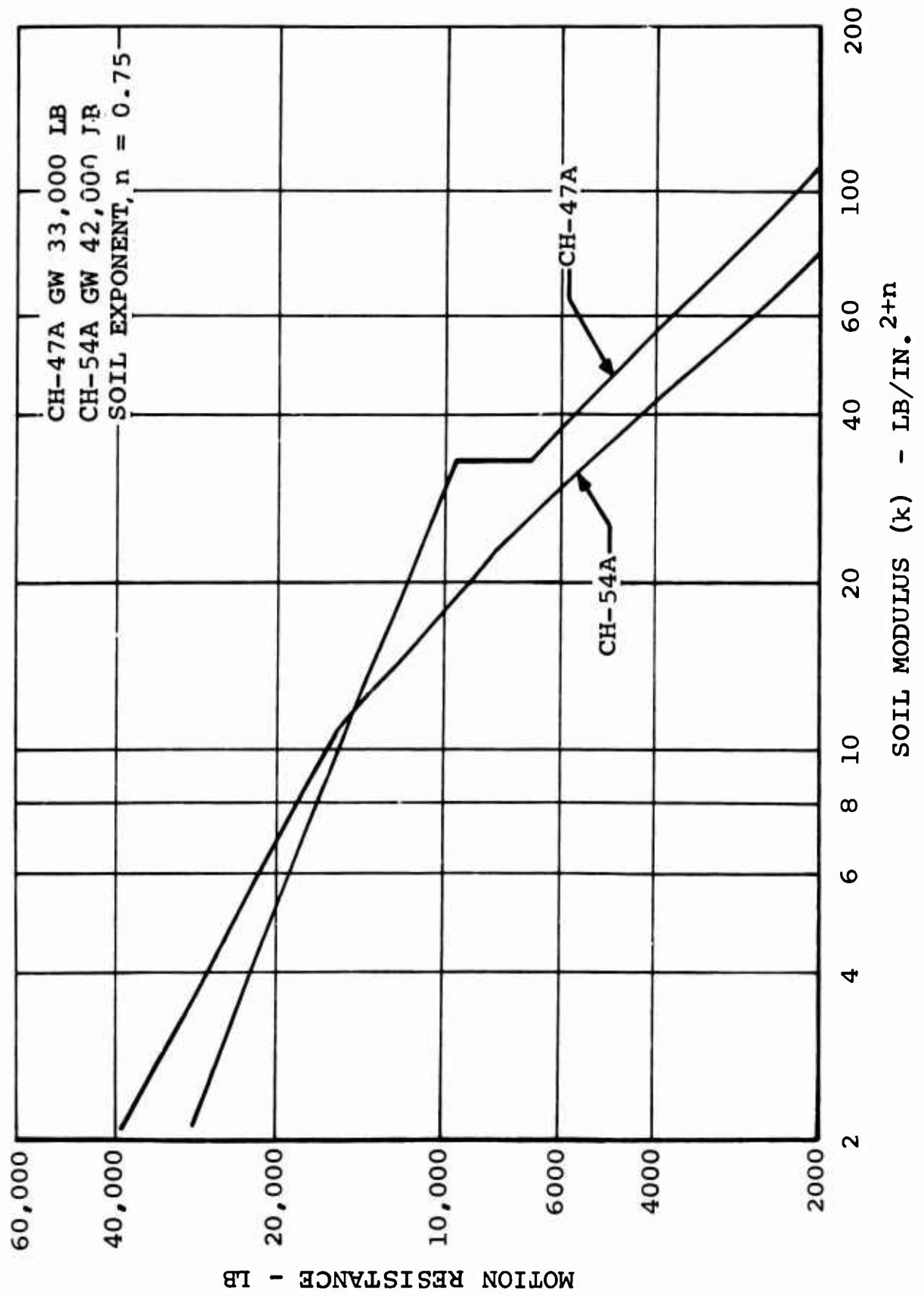


Figure 73. Motion Resistance of CH-47A and CH-54A in Soft Soil

downwash Effects

In order to hover, a VTOL aircraft moves a mass of air towards the ground. This is true for all forms of VTOL aircraft, from helicopter to jet lift. The difference between the various configurations is in the velocity and area of this mass, known as the "downwash".

For a hovering rotor (see Figure 74 below), the induced velocity, v_i , as defined by simple momentum theory is expressed as

$$v_i = \sqrt{\frac{1}{2\rho} \cdot \frac{T}{A}} = \sqrt{\frac{D_L}{2\rho}} \quad (13)$$

where D_L is the disc loading T/A in pounds per square foot.

In practice, the downwash varies across the rotor disc, and the peak value is affected by the number of rotor blades.

Ideal downwash velocity as a function of disc loading is plotted in Figure 75. The downwash passes through the rotor disc at a velocity, v_i , the slipstream contracts, and the downwash velocity increases to a maximum of $2v_i$, or twice the

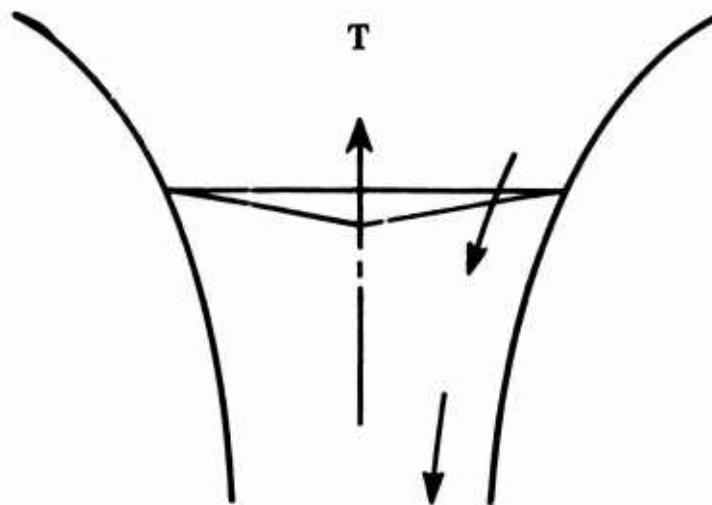


Figure 74. Induced Airflow Through a Hovering Rotor

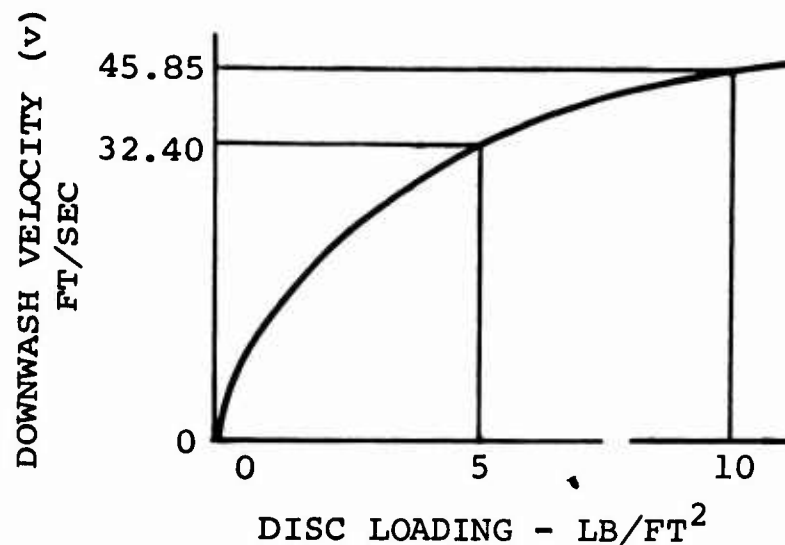


Figure 75. Downwash Induced Velocity at the Rotor Disc (Out of Ground Effect)

velocity through the disc. The downwash subsequently dissipates some distance below the rotor. If the rotor is operating close to the ground, the induced velocity is reduced, and the flow is modified as shown in Figure 76. The Army Corps of Engineers has measured the downwash velocity profiles for several Army helicopters operating in ground effect. A plot of three typical measurements is shown in Figure 77. The dust and debris stirred up by the downwash during hover create three major problems:

1. Visibility limitation for pilot and ground crew.
2. Safety of ground crew.
3. Engine foreign object ingestion.

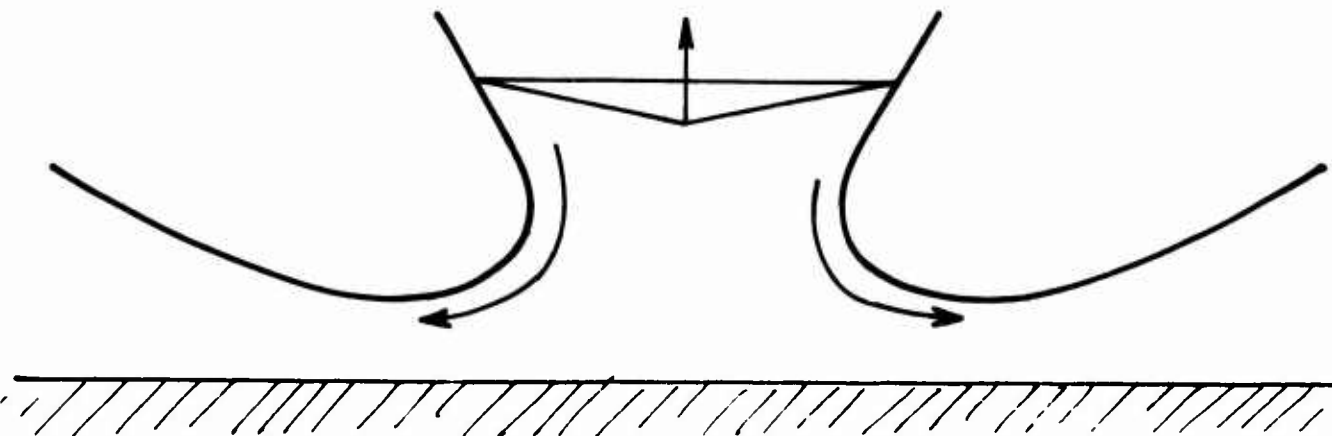


Figure 76. Airflow Through a Rotor in Ground Effect

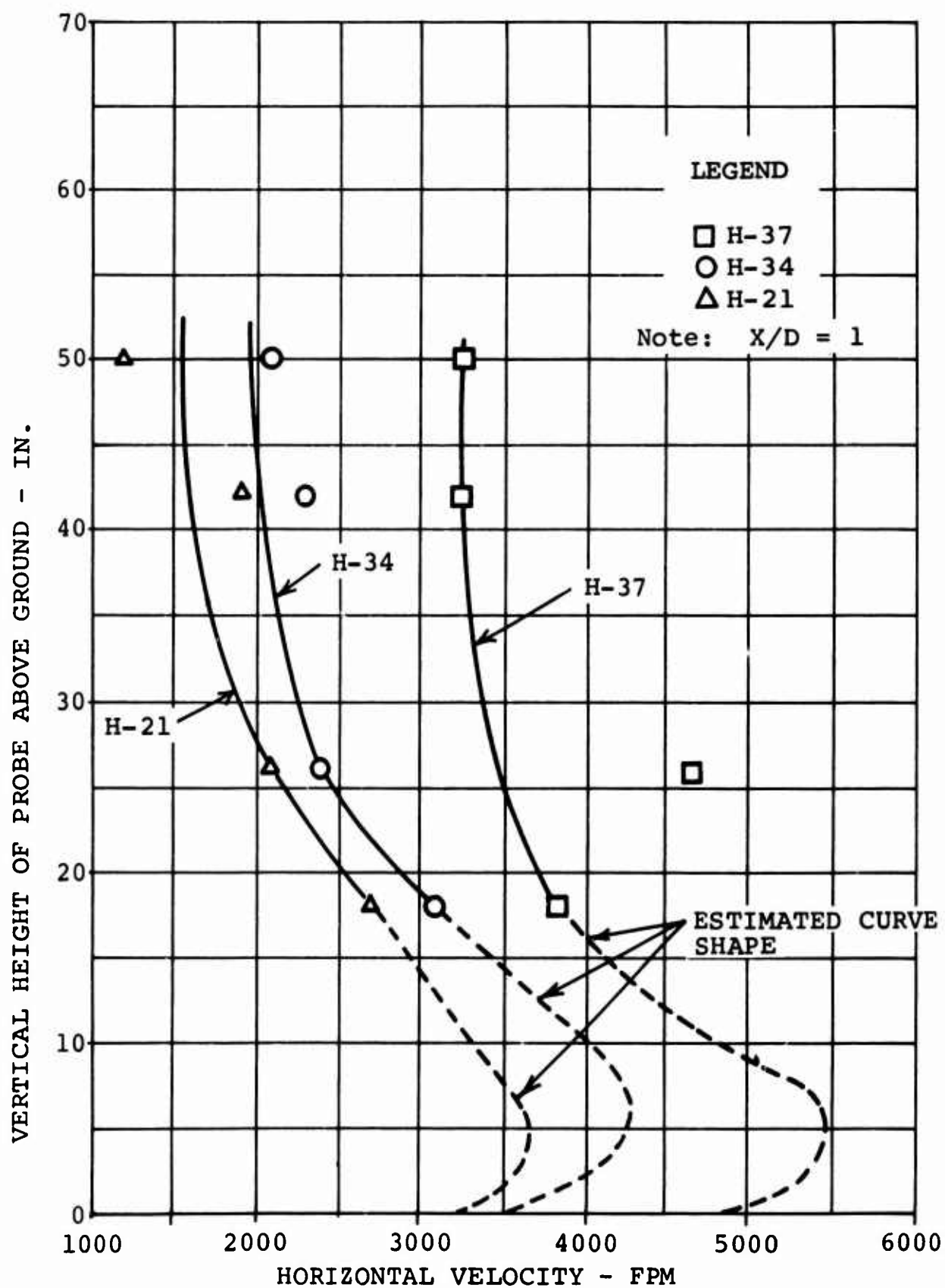


Figure 77. Velocity Profiles - One Rotor Diameter from Center of Rotor (Fort Rucker Tests)

Visibility Limitations - The study conducted by the Corps of Engineers on helicopter downwash blast effects indicates that if the air velocity close to the ground exceeds 1200 feet per minute over dry fine sand, and 1800 feet per minute over a dusty surface, a dust hazard condition will result. Figures 78 and 79 indicate the effect of disc loading on pilot visibility for vehicles with a gross weight of 17,500 pounds. These data were obtained from an analysis of the downwash environment of the Vertol Airborne Artillery Fire Support System (AAFSS) tilt-wing. It is interesting to note that the study indicated similar cloud effects for dry sand and water (spray) and dust and powdered snow. For a helicopter of given disc loading, the data in Figures 78 and 79 may be replotted as a function of helicopter percent airborne. In this form, the data are useful in selecting landing gear motion resistance criteria, since, in order to taxi, the helicopter must apply some rotor thrust; refer to the LOAD ACQUISITION section.

Another visibility problem concerns the safety of the ground crew in attaching an external load while the helicopter hovers above them. Figures 80 and 81, also from the Vertol AAFSS study, compare cloud height and aircraft altitude for tilt-wing AAFSS vehicles with those for the H-37 helicopter. These data may be used in determining the length of cable required in winch-up load operations.

Because of its greater size, the heavy-lift helicopter (HLH) will produce a cloud larger than those indicated in the above-cited illustrations. Further analysis of the problem is necessary to accurately determine the cloud pumping characteristics of the HLH.

Ground Crew Safety Consideration - When the aircraft is hovering over unprepared sites, stones and debris will be lifted and thrown out radially from underneath the helicopter. Figure 82 shows the maximum stone size that might be thrown by the downwash from a tilt-wing AAFSS and from the H-37 helicopter. Also included is an estimated curve for the HLH. The injury to personnel which these stones could cause is indicated in Figure 83.

Particle trap data presented in Reference 6, indicate that maximum-size stones are transported at aircraft heights above the ground equal to 5 to 10 percent of the fully developed slipstream diameter. For the H-37, this is about 5 feet; for a typical HLH, it would be about 6.5 feet.

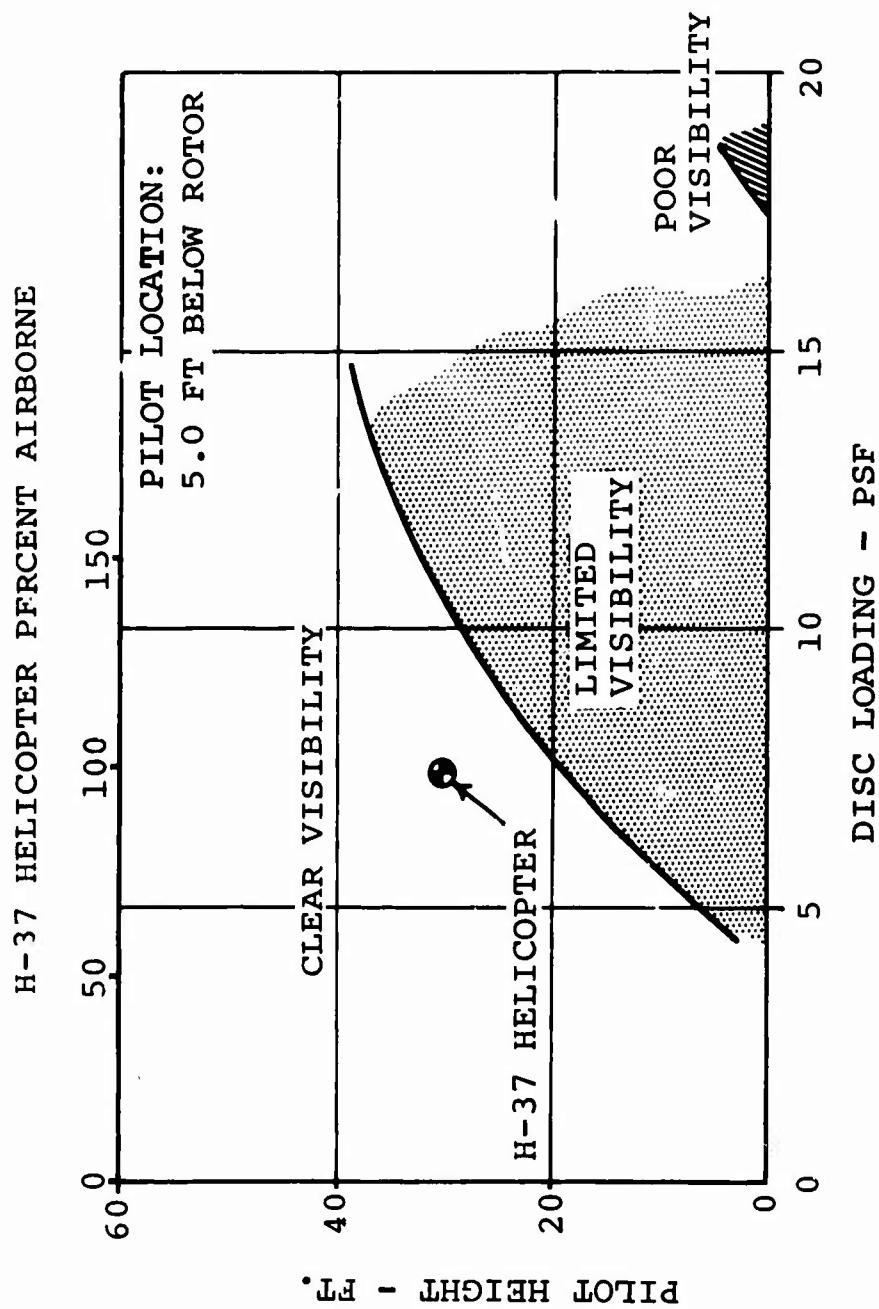


Figure 78. Variation of Pilot Visibility Conditions with Disc Loading and Aircraft Altitude for a 17,500-Pound Helicopter. Terrain: Water or Coarse Sand

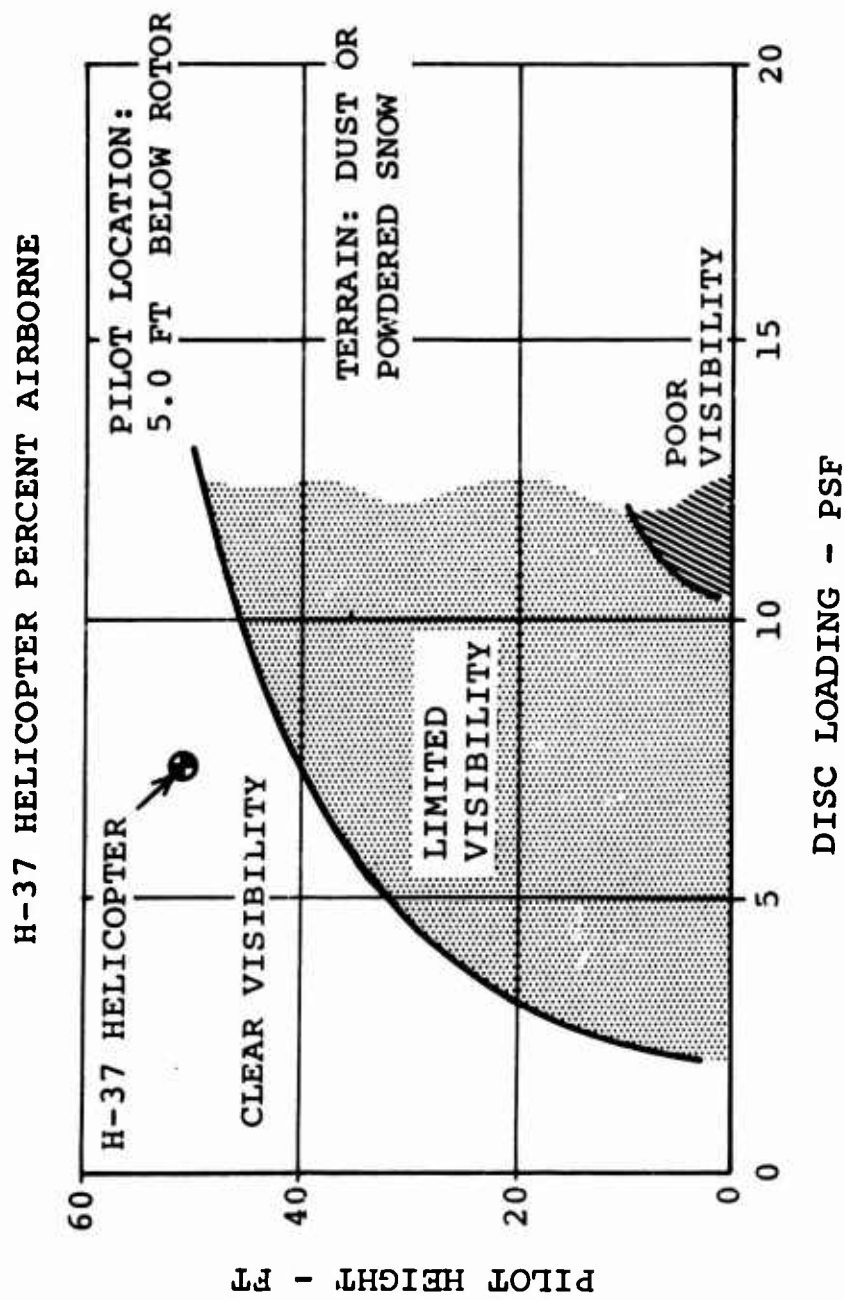


Figure 79. Variation of Pilot Visibility Conditions with Disc Loading and Aircraft Altitude for a 17,500-Pound Helicopter. Terrain: Dust or Powdered Snow

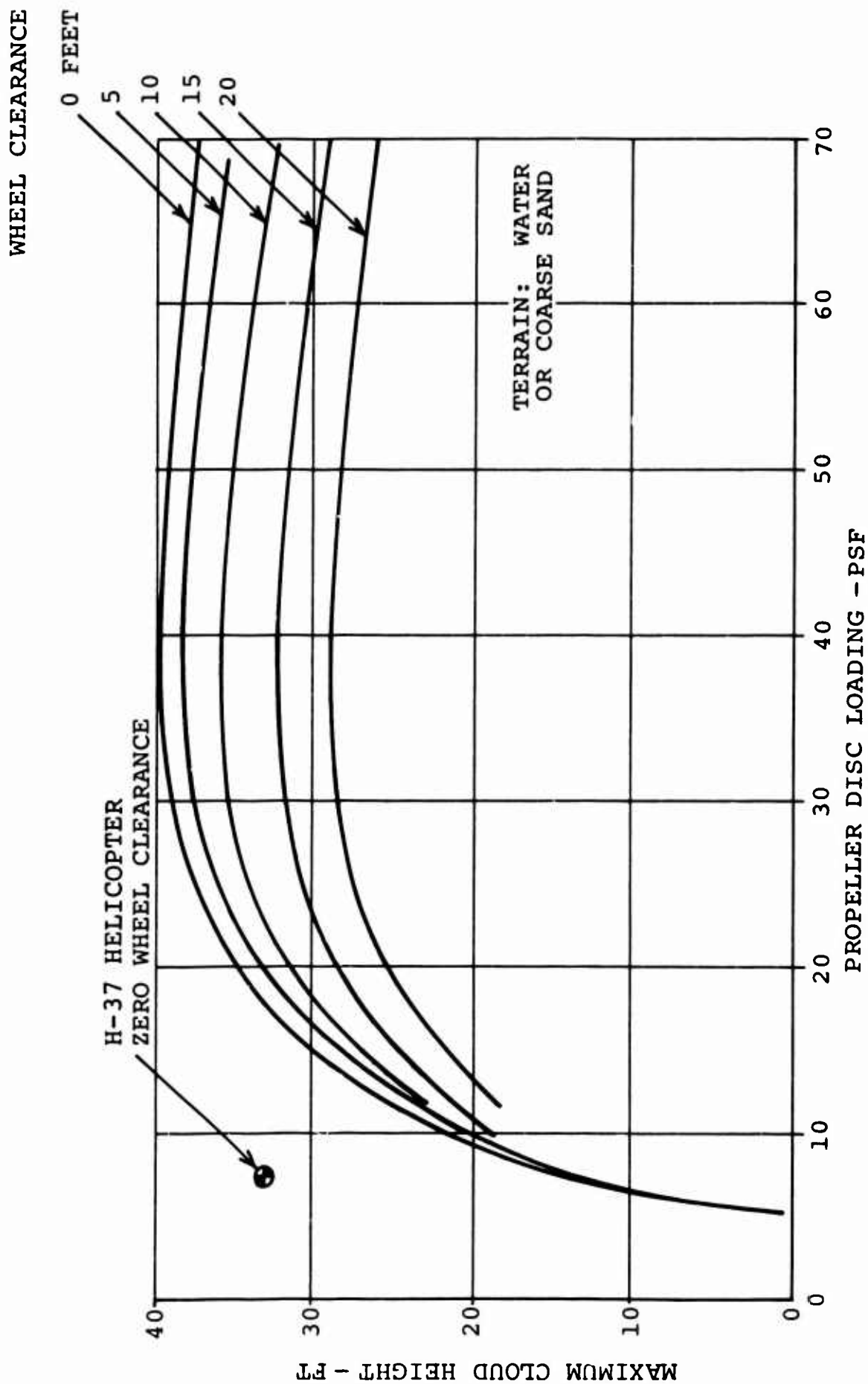


Figure 80. Maximum Cloud Height Generated by a 17,500-Pound Tilt-Wing VTOL Aircraft as a Function of Aircraft Altitude and Disc Loading. Terrain: Water or Coarse Sand

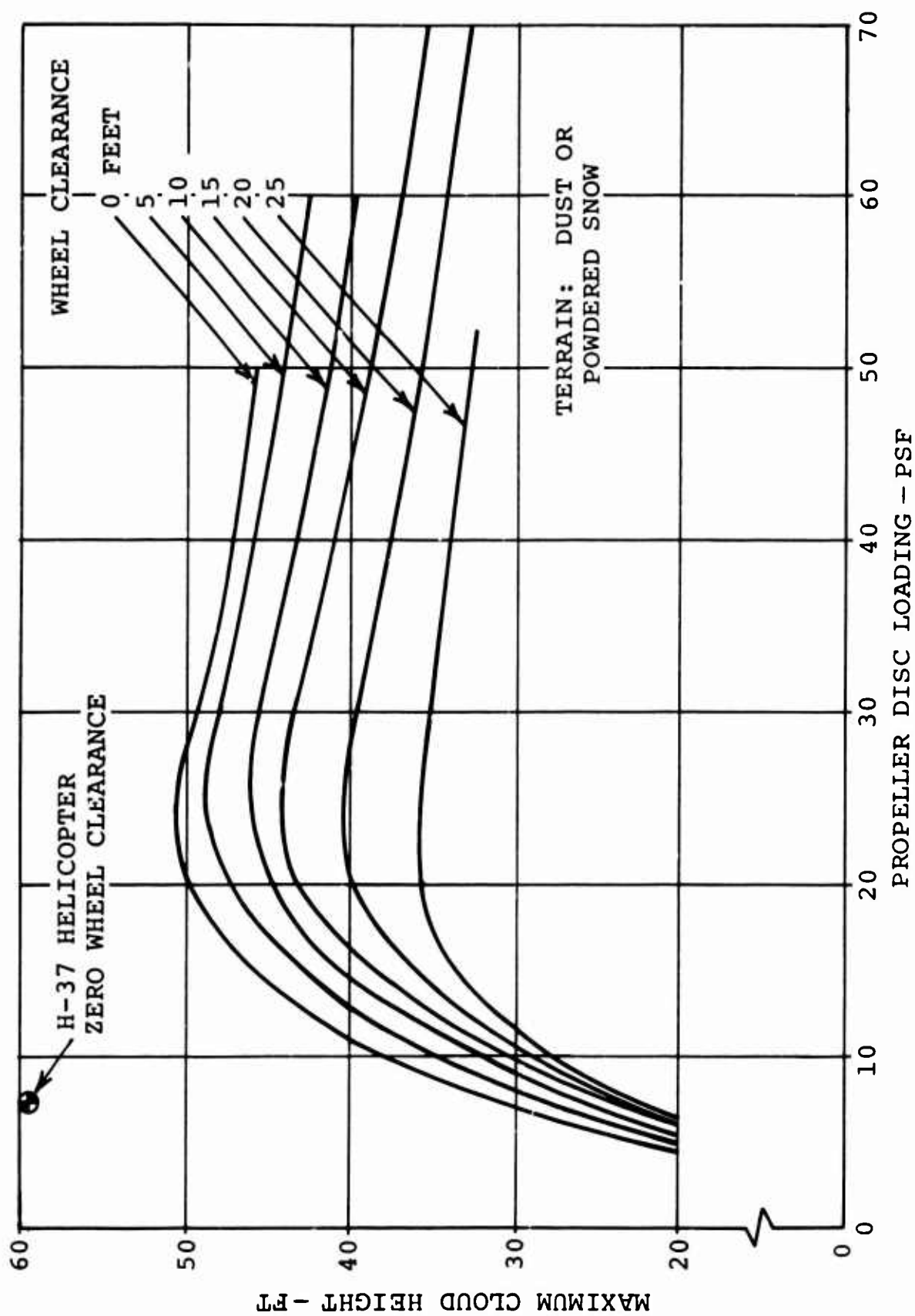


Figure 81. Maximum Cloud Height Generated by a 17,500-Pound Tilt-Wing VTOL Aircraft as a Function of Aircraft Altitude and Disc Loading.
Terrain: Dust or Powdered Snow

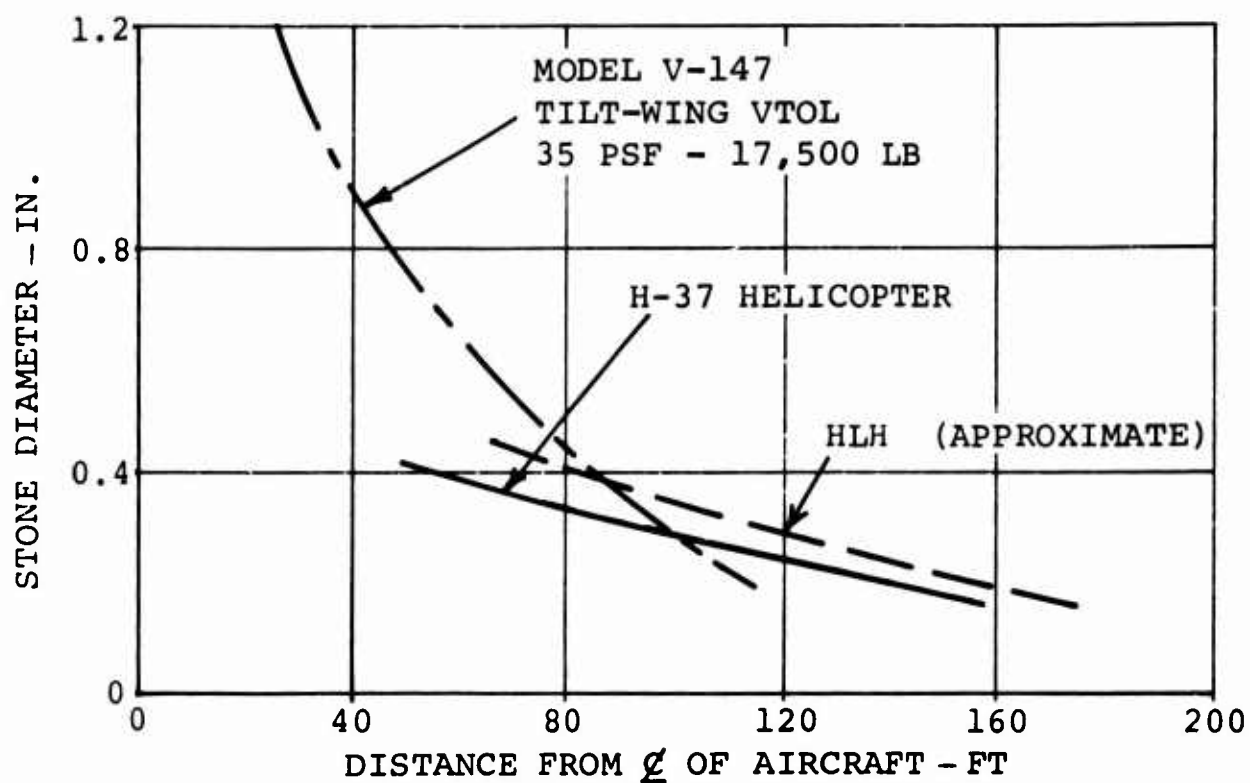


Figure 82. Maximum Stone Size Transported by Rotor Downwash

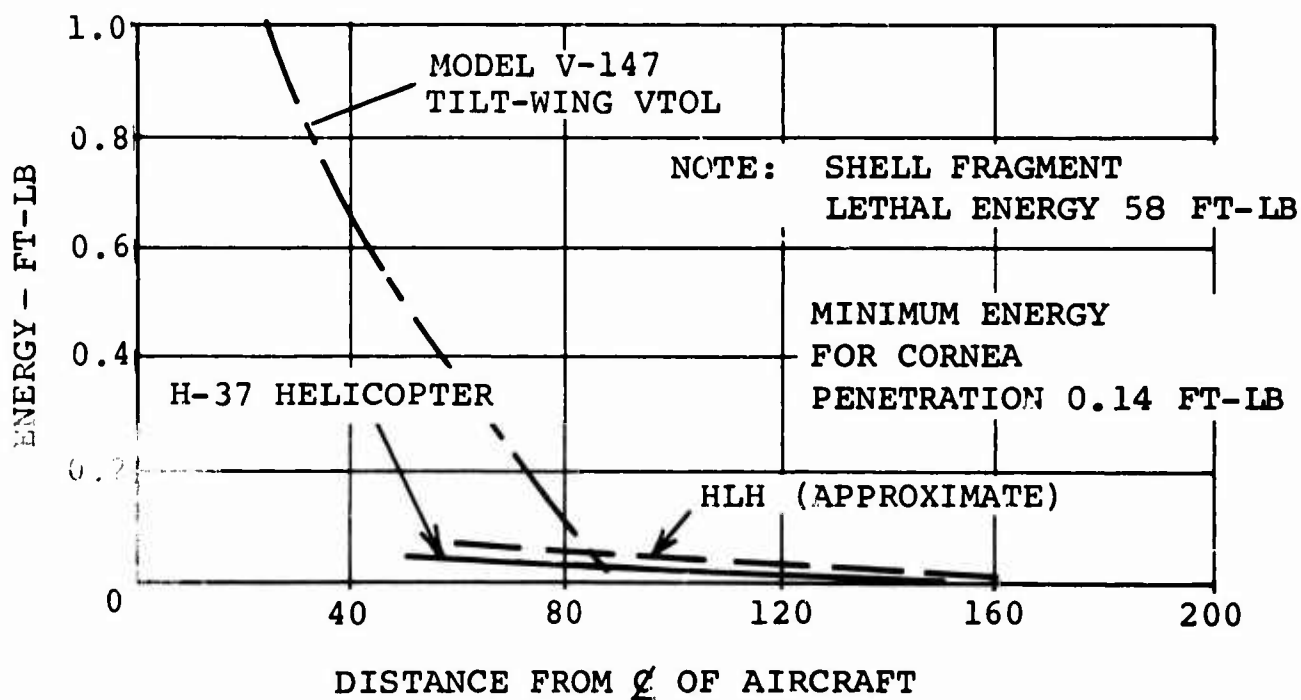


Figure 83. Kinetic Energy of Stones Transported by Rotor Downwash

A hazard also exists from the movement of large-drag-area, low-density objects such as tree limbs, planks, and empty containers. Analysis of the behavior of an empty 55-gallon drum in proximity to an H-37 resulted in the curve shown in Figure 84.

Engine Foreign Object Ingestion - This problem is not within the scope of this study.

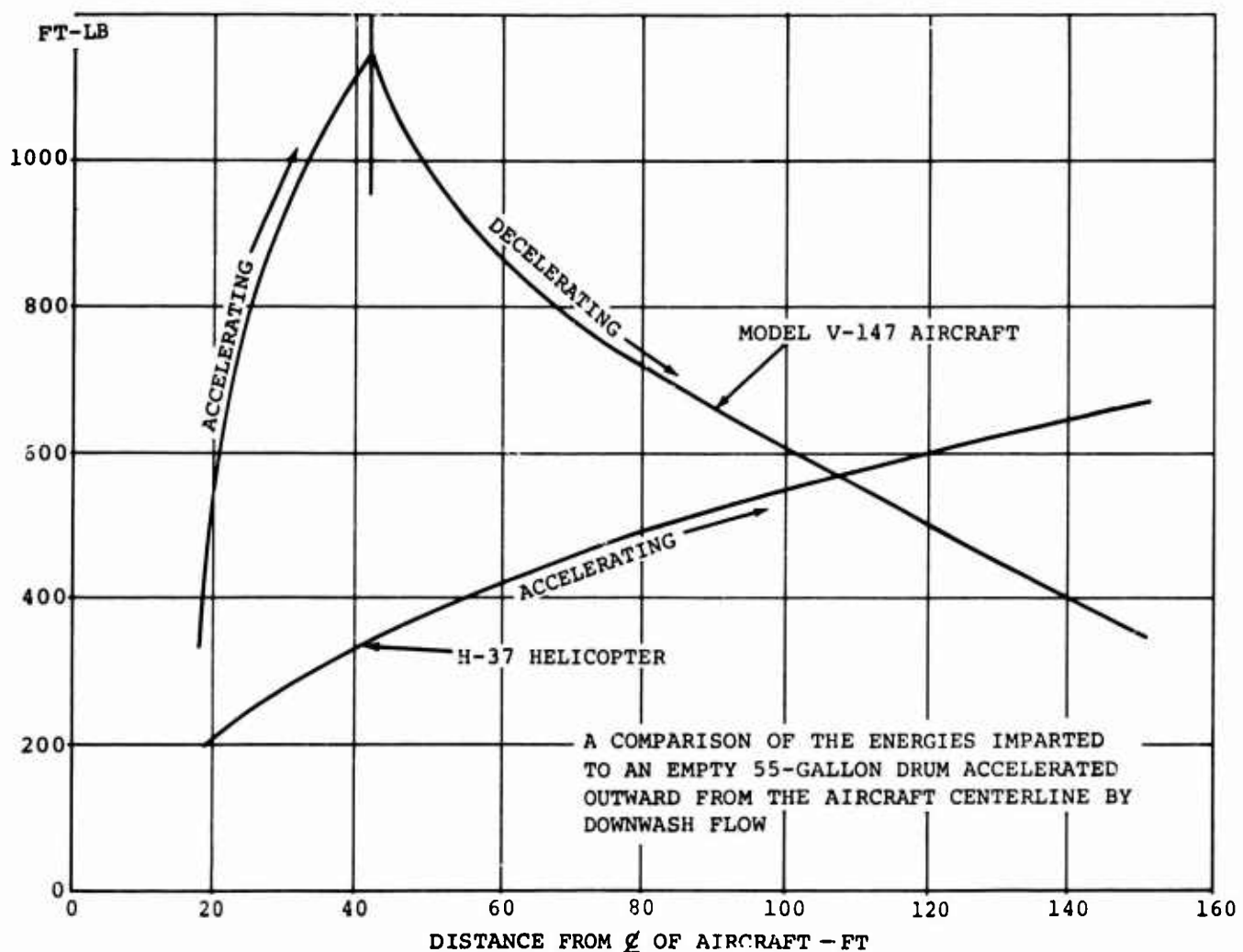


Figure 84. Kinetic Energy Imparted to Empty 55-Gallon Drums by Rotor Downwash

STATIC ELECTRICITY

For the aerial crane mission, static electricity accumulated in flight can constitute a serious hazard during ground handling. This hazard involves both the possibility of injury to ground personnel performing cargo hookup or release duties and the possibility of damage to suspended cargo (which might include missiles). Radio interference will also result from

static discharge and, while this is of secondary importance compared with the problems just mentioned, a solution to these will also provide a solution to the interference problem.

Static electricity may be accumulated during flight from any of the following sources:

1. Efflux of ionized hot exhaust gas.
2. Friction of air particles against the aircraft skin.
3. Impact of sand particles against the aircraft skin.
4. Breaking up of snowflakes impinging on the aircraft.

Of these sources, 3 and 4 are by far the greatest contributors. As long as the air humidity is high, the static charge dissipates easily. Under dry snow and dry sand conditions, dissipation is very slow and the charging phenomenon reaches its most pronounced form.

For the purposes of this study, it is sufficiently accurate to consider that the same energy level of approximately 1 millijoule is required to cause (1) ignition of fuel, (2) shock to ground personnel, and (3) ignition of weapon squibs. Compare this with the level of energy - 500 joules - delivered by a 1-million-volt spark. Voltages of this magnitude can easily be acquired by a large helicopter, and discharge sparks up to 3 feet in length have been observed in such circumstances (References 8 and 9).

The safe level of 1 millijoule limits the maximum allowable helicopter voltage to approximately 1700 volts. Since passive discharge devices cannot reduce the voltage to this level, a forceful discharge is required.

At present, one of the most successful devices in this field is the equipment fitted on the CH-47A. It is expected that it will keep the helicopter discharged to a 300-volt level. This device is a must for external cargo handling over snow and dry sand, because discharging the helicopter by a static line dropped to the ground is impossible. Snow and dry sand are insulators, and the charges cover large surface areas where they "sit captive," or are distributed through the volume of surrounding snow or sand cloud. Over the sea, a static line, dropped into the sea or to a metal

ship's hull, will discharge the helicopter completely. Standard procedure when approaching an air-sea crash area surrounded by spilled fuel is to drag the rescue gear through the sea in order to avoid any chance of producing a static spark.

LONG-LANDING-GEAR HELICOPTERS

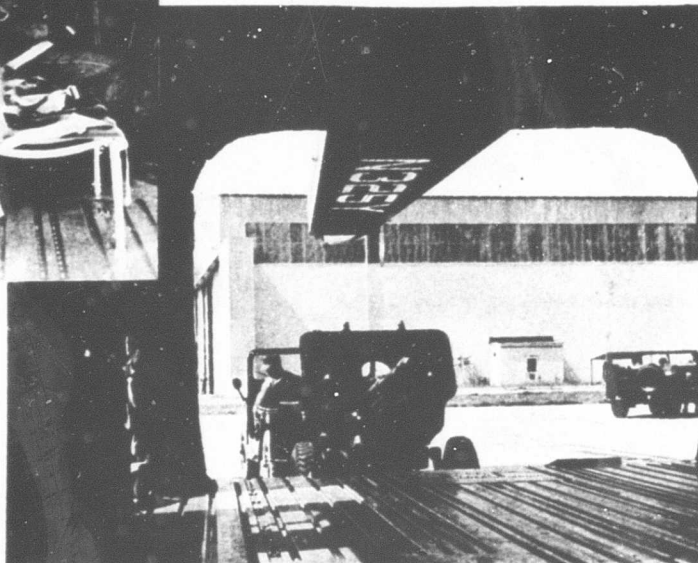
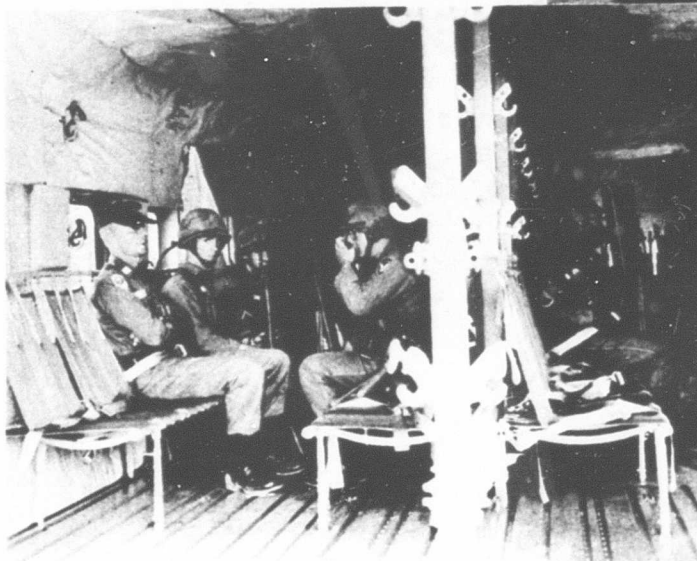
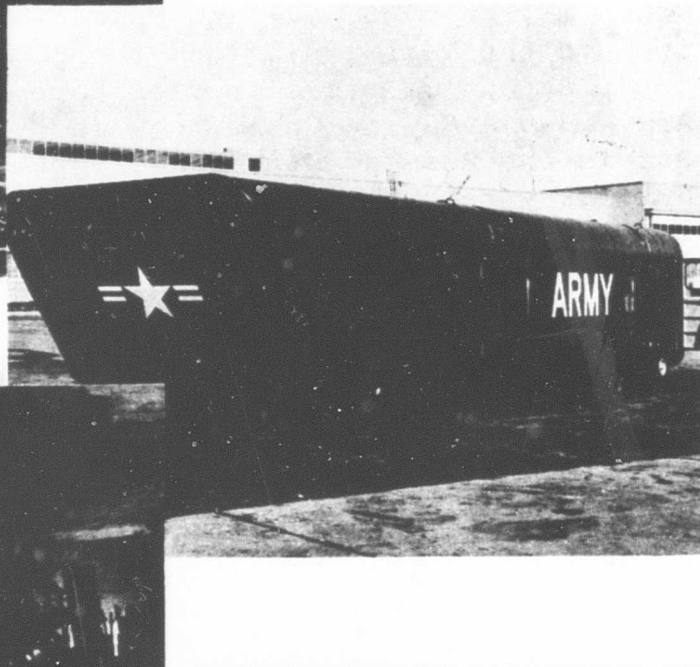
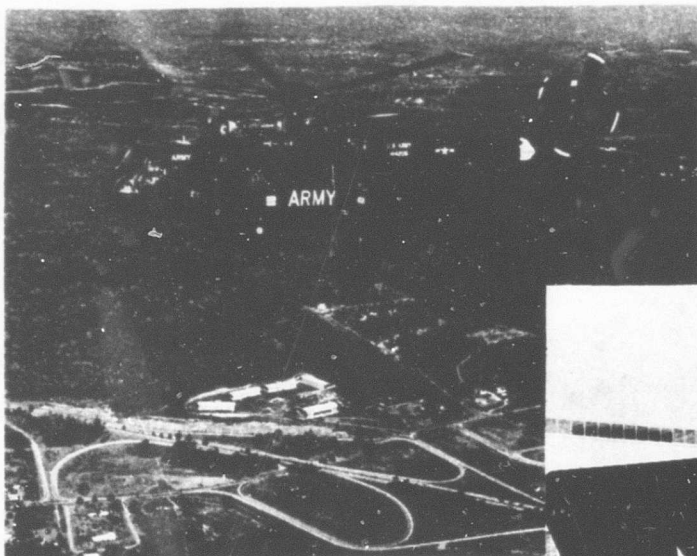
GENERAL CONSIDERATIONS

Helicopters with landing gears long enough to permit external loading and discharging while the helicopter is on the ground are of interest because of the variety of handling techniques which may be used. Design concepts which have been studied include the Vertol H-16 and the Hughes XH-28. Practical applications of these studies have been embodied in the Army CH-54A Flying Crane, now under operational evaluation, and in the Russian MIL-10 helicopter. The CH-54A utilizes an auxiliary removable pod for transportation of troops, as shown in Figure 85; the MIL-10 employs an external platform suspended from the landing gear structure (see Figure 86). Both systems have been effectively demonstrated. Although evaluation data for the MIL-10 platform system are not available, considerable knowledge is available on the pod-configured CH-54A helicopter.

Pods and platforms usually are rigidly attached to the helicopter. This has several advantages: air speeds are not restricted by the stability of the load, and attachments may be designed to be more reliable than for suspended loads. Operational benefits of pod and platforms depend very strongly on developing an entire cargo handling system to utilize them. Load acquisition and deployment times for pods are currently very high, and although they can undoubtedly be reduced, the value of extending the pod concept to many types of loads depends upon a detail tradeoff study between airspeed and load acquisition time. Widespread use of the platform system also depends on the method of acquiring loads. Loads may be moved on and off a platform which remains attached to the helicopter, or preloaded platforms may be used.

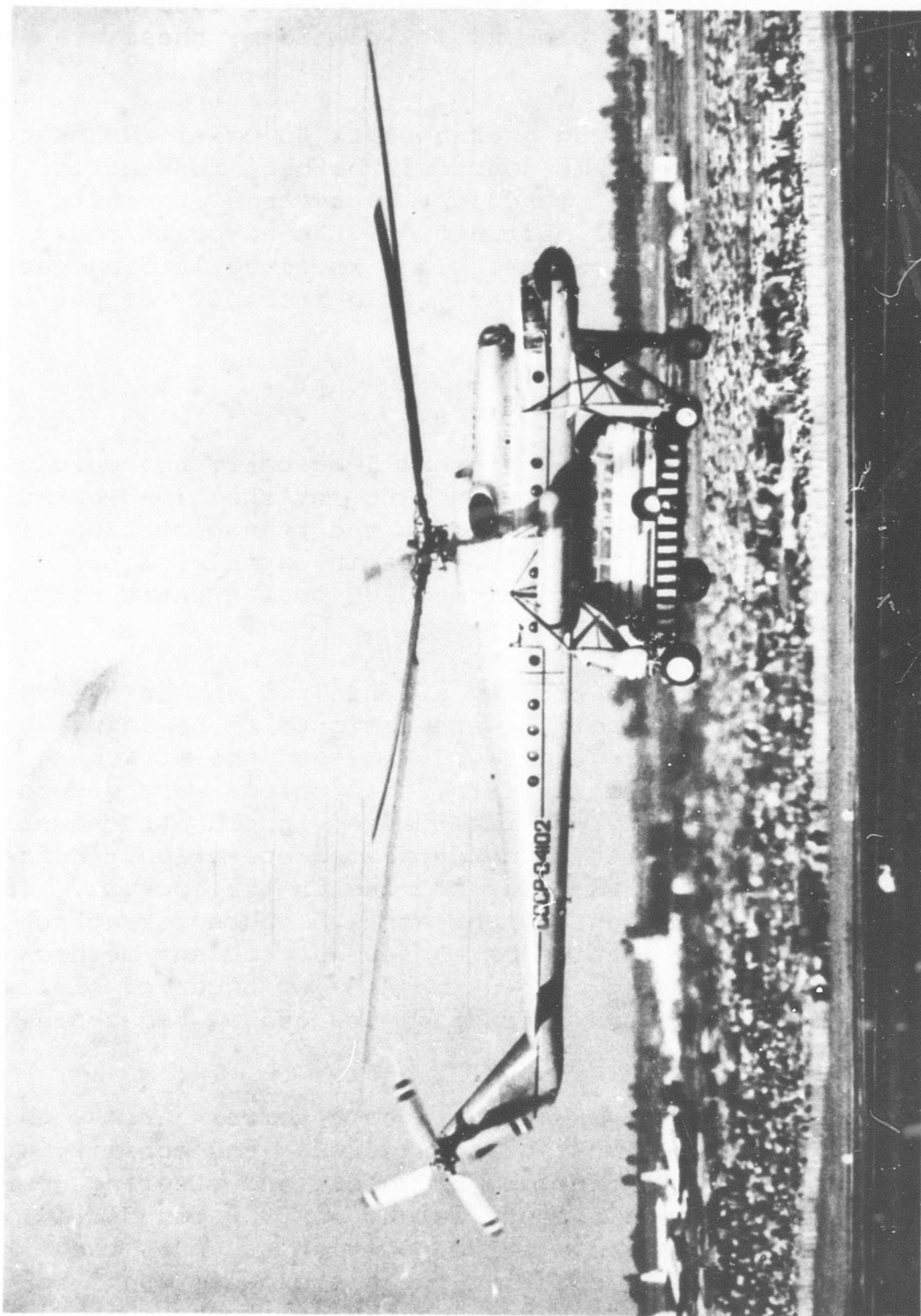
KNEELING LANDING GEAR

When attaching a pod or platform to a crane-type helicopter, it is necessary either to lift the pod to the helicopter or to lower the helicopter to the load. This results from the necessity to provide sufficient ground clearance to enable the landing gear to pass through its entire travel on landing without grounding the load. The clearance should be sufficient to allow landings on uneven terrain and to prevent grounding in the event of a flat tire.



Verti-Flyte Magazine

Figure 85. CH-54A Pod



Aviation Week and Space Technology
Figure 86. Russian MIL-10 with External Loading Platform

The CH-54A uses a combination of kneeling landing gear and extendable load lifters. The MIL-10 helicopter uses only extendable load lifters to pick up its platform; these are clearly shown in Figure 87.

The use of a kneeling landing gear appears to offer advantages, such as simplicity, but it is doubtful whether, in practice, this is the best approach. Load lifting systems are quite simple and, in the event of malfunction, the aircraft could still be used for other missions. If a kneeling landing gear suffers a malfunction, the aircraft would probably be put out of commission.

EXTERNAL PODS

The CH-54A was designed as an external load-carrying vehicle. Except for flight crew accommodation, no internal load-carrying capability exists. In order to permit the transportation of men, it was necessary to introduce a cabin capable of being attached to existing hard points embodied on the basic airframe for external load-carrying systems.

In order to facilitate the fitting of this pod to the airframe, the existing four pickup points were designed to be adjustable, with a vertical travel of 8 inches. Provided the attachment was made on good level terrain, no problems were encountered; however, difficulty was experienced in pod attachment on rough terrain. The pod attaching/detaching operation required five men, one for each hard point and one in the cockpit. The time was 4.5 minutes for detachment and 1.5 hours for attachment. Although design details of the pod attachment method are not available, a review of current methods of securing similar systems to prime movers indicates that the quoted times could be considerably reduced.

If helicopter/pod systems are used in soft terrain areas, the question of pod mobility must be considered. Pod mobility will mean a weight penalty in the form of wheels and steering gear. When so-equipped, the pod's empty weight of 3900 pounds will still need considerable manpower to position it under the helicopter. One possible solution to this problem would be the introduction of a winch system on the helicopter, capable of pulling the pod into position for pickup.

The other approach is to provide the helicopter with good ground handling characteristics in soft soil. Such a capa-

bility would naturally increase the weight of the helicopter, since large high-flotation tires would be necessary in order to reduce the motion resistance and to enable ground maneuvers to be made with precision. Accuracy in positioning the pod is a major factor in attachment time.

The pod concept has several important advantages. The pod may be rigidly attached to the airframe by multiple points; this enables the aircraft to fly at high speeds without load stability limitations. The pod attachment is much more reliable than a slung load, and it is ideal for transportation of valuable cargo such as men, radar racks, etc.

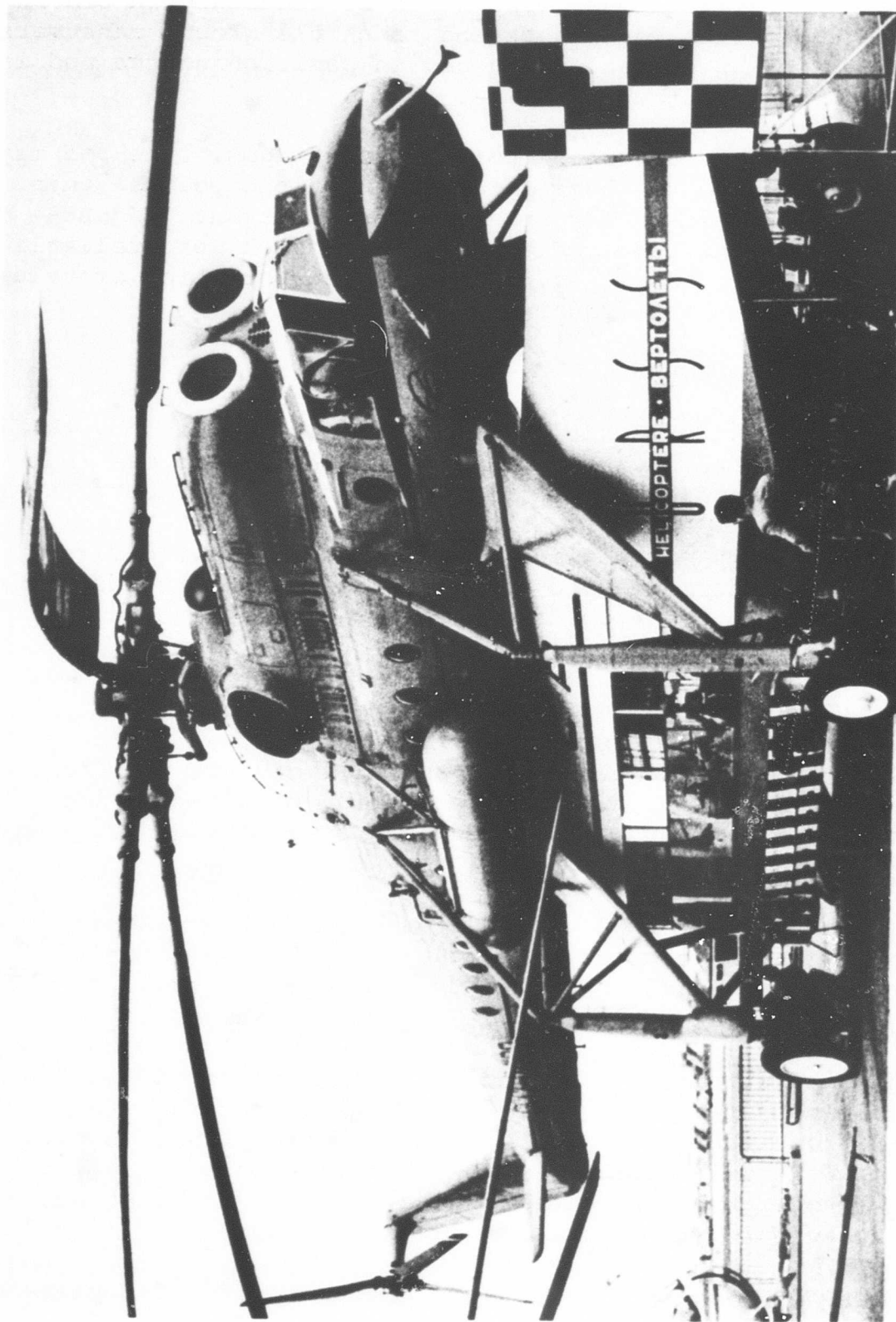
EXTERNAL LOAD PLATFORMS

External load platforms have been studied in the past by the Hughes Tool Company, but the only flight vehicle to use this concept is the Russian MIL-10 helicopter shown in Figure 86.

External platforms may be used in two ways. With the first method, the platforms may be preloaded and then attached to the aircraft at the appropriate time. Having delivered the load, the helicopter may drop the platform and return for another load. This technique was demonstrated by the MIL-10 helicopter at the 1965 Paris Air Show; it is shown in Figures 86 and 87. It permits maximum utilization of the helicopter, but it creates a substantial logistics problem in the availability of platforms which would, of necessity, be quite large (typically, for the HLH, 36 feet long and 12 feet wide).

With the second approach, the platform remains permanently attached to the helicopter. The platform is then loaded and unloaded while the helicopter waits. It may be argued that this has no advantage over a transport helicopter where the load is carried internally. However, the external platform permits a great flexibility of loading and unloading, since the load is accessible not only from the rear, but also from the sides and possibly from the front. Loading can be accomplished by standard forklift trucks, and the platform may be raised (by the load lifters or kneeling landing gear) to truck-bed height, thus facilitating rapid handling of palletized loads.

Another approach to the loading and unloading of fixed platforms is to use trains of loaded dollies connected together and pulled by a tractor. If the helicopter has a through-



Aviation Week and Space Technology
Figure 87. Russian MIL-10 with Pod Loaded on Platform

loading capability (i.e., is equipped with quadricycle landing gear), the tractor may pull the train onto the platform, where it is uncoupled and tied down. At the delivery point, a second tractor pulls the train off, allowing the helicopter to return for another load.

Platforms may be converted to pods for personnel transportation by the addition of side enclosures and troop seats. As with the pod, the platform must be lifted clear of the ground during operation, or a ramp must be fitted. Attachment of the platform must be made on the aircraft side of the landing gear shock strut. If the platform is attached to the axles or lower end of the shock strut (a deceptively simple approach), the accelerations experienced by the cargo and the loads experienced by the wheels and tires during landing impact would be excessive.

SLUNG-LOAD METHODS

Long-gear helicopters can use the same slung-load techniques and devices as short-gear helicopters of conventional design, and can perform the same services, but with certain advantages.

Most of the safety problems in conventional handling methods for slung loads result from the fact that the helicopter hovers at low altitude for pickup and delivery. If long-gear helicopters land and then taxi over a load to be picked up, or away from a delivered load, or if they park for servicing by ground equipment, the safety problems are substantially reduced.

With a long landing gear, large loads in nets or in pre-tied load units and large items in slings can be loaded (and discharged) with the aircraft on the ground and then carried as suspended loads (see Figure 40). This technique appears to be unfeasible with short-gear helicopters unless the suspension lines from the helicopter are of such length as to allow alongside loading and unloading of suspended cargo. The suspension system could hoist the load up against buffer pads on the bottom of the fuselage to prevent swaying. Such loads would have to be in containers, or special provisions would have to be made to obtain maximum system productivity.

It should be recognized that if multiple suspension points are used, balance problems will be encountered, and the automatic balance feature of single-point suspension will be lost,

as described in previous sections of this report.

If the suspended loads can be elevated clear of the ground and secured, running takeoffs and landings may be used - a mode of operation not possible with short-gear helicopters with external loads.

EFFECTS OF EXTERNAL LOADS ON HELICOPTER HANDLING, STABILITY, AND VIBRATION

VERTICAL BOUNCE

Divergent vertical oscillations, which are sometimes termed the collective bounce, have been observed on all major helicopter configurations in hover and forward flight. They consist of rapidly divergent vertical oscillations of moderately high frequency (3 to 4 cycles per second) which are completely uncontrollable by any deliberate maneuvering of the pilot's collective stick. Although this problem is common to all helicopters, it is often greatly aggravated during external cargo carrying missions when a particularly unfavorable combination of external load and sling configuration is used. Published pilot's comments (Reference 12) indicate that these oscillations remain divergent as long as the pilot effectively maintains himself in the collective control loop.

Vertical Helicopter Motions with Locked Collective Pitch

The vertical motions of a hovering helicopter are defined by a two-degree-of-freedom system comprising rotor flapping and vertical fuselage displacements. It is essentially a highly damped equilibrium state, and a vertical disturbance will result in rapidly damped oscillations at the frequency close to the fundamental flapping frequency. The addition of an external load affects the basic frequency of the oscillating modes; however, it does not change the basic damped character of these oscillations over the entire range of the load-sling vertical frequencies, as shown in Figure 88.

Vertical Helicopter Motions with Unlocked Collective Control

Figure 89 shows the basic mechanical features of a typical collective control actuator which define the dynamic behavior of the combined helicopter system with an unlocked collective control stick. The stick cg position, δ , is an important dynamical factor. It determines the mode of coupling between the vertical helicopter motion and the resulting stick motions. If the stick cg (including the effects of the linkages) is in a forward position, this combined system has an oscillatory mode in which the fuselage oscillates about a stick position fixed in space, with the oscillatory frequency defined by the stick sensitivity (i.e., the stick capability to develop

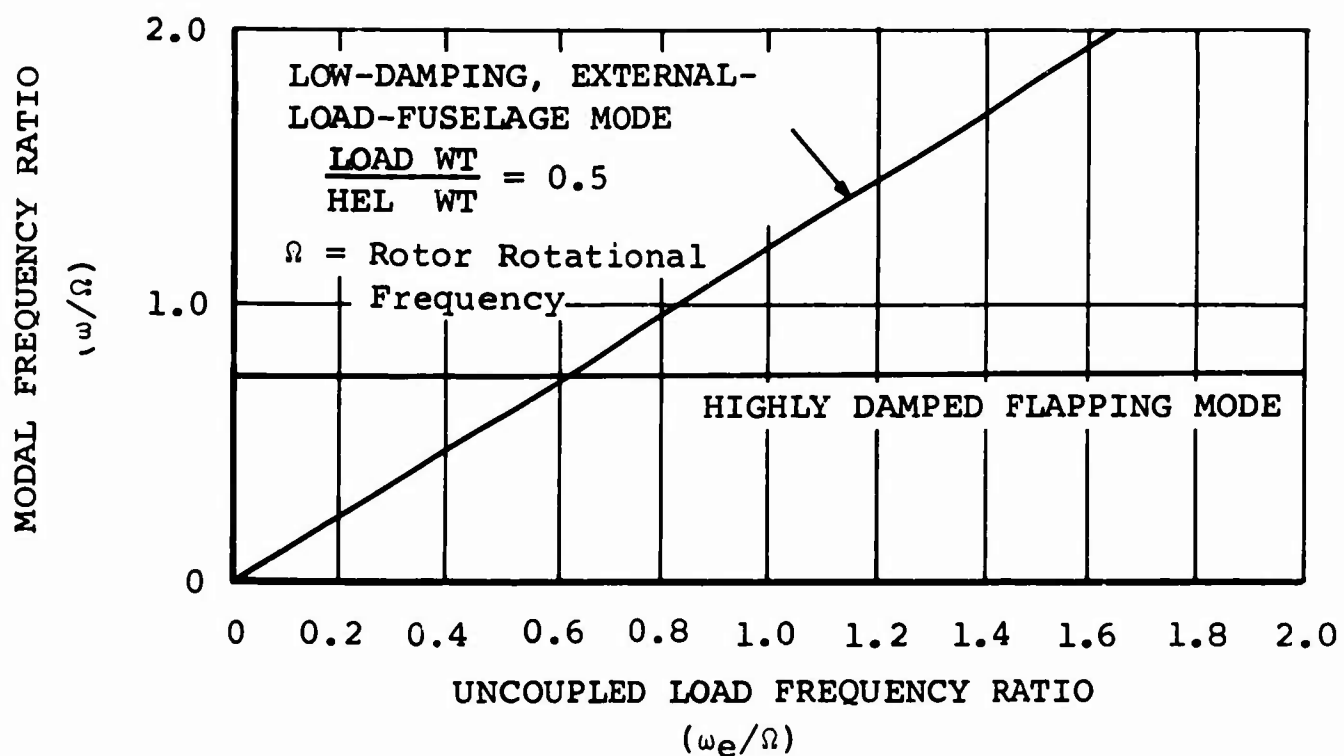


Figure 88. Fundamental Frequencies for Locked Control

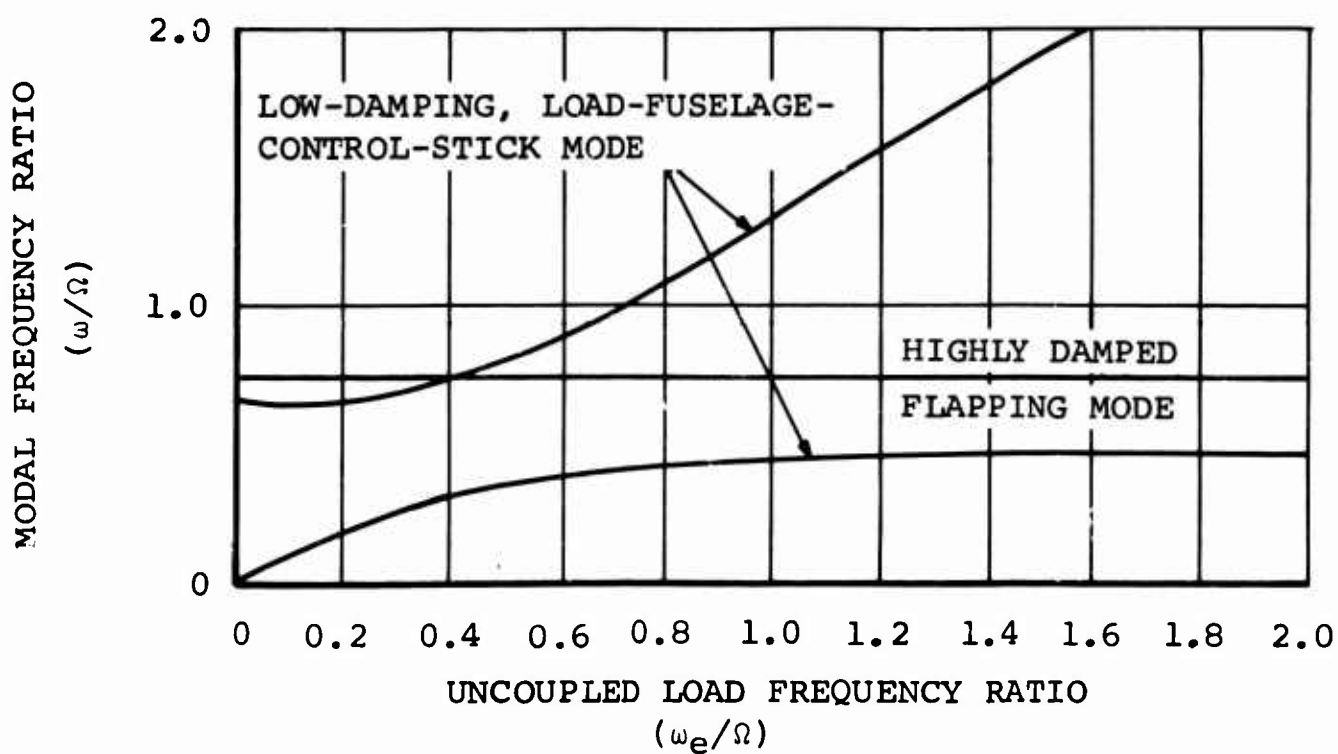


Figure 89. Fundamental Frequencies with Unlocked Control

helicopter acceleration per inch of the stick displacement). The stick motion gradually disappears as the cg offset, δ , is reduced; at $\delta = 0$, the stick motion will not be excited by the fuselage. With an aft cg offset, no oscillatory mode exists in the system shown in Figure 89, but a pure divergent mode appears. One significance of these modes is in their effect on the pilot's feel of the collective control in a sustained vertical maneuver. With the cg offset in the forward position, the collective control will stiffen in such a maneuver, whereas an aft cg position will lead to a softening effect. While actual designs of collective control actuators seldom take explicit account of these effects because of a small effective control mass (of the order of 5 pounds), most helicopters have a slight forward stick cg. This results from the fact that the largest part of the effective control mass is contained in the stick handle, which typically remains in the forward position.

The vertical behavior of a simplified helicopter system with unlocked collective control stick and a small stick-centering spring is shown in Figure 89. A forward stick cg was assumed, to obtain the frequency plot of Figure 89, so that only the oscillatory modes are represented here. The oscillatory modes thus remain stable when the control stick is unlocked, although the frequency distribution is generally altered.

The Mechanism of the Unstable Vertical Oscillations

The foregoing discussion illustrated the fact that the basic mechanical linkage features of a typical collective control system do not by themselves give an unstable system. Additional destabilizing features must be introduced to give instability of the rapidly divergent type characteristic of vertical bounce. The control system here introduces a powerful means by which the vertical motion may be destabilized if the basically open control loop of Figure 90 is effectively closed by the pilot, as shown in Figure 91. The fundamental parameters in this destabilization through the closed loop system with the pilot are the gain (defined by the stick sensitivity) and the phase difference (between the fuselage motion and the thrust due to collective control displacement) that will be introduced by the pilot when he enters the control loop. This leads to a generalized representation of the collective feedback loop where a system with the basic frequency, ω_s , has a displacement feedback with an inherent time delay. The time delay in this system (see Figure 91) leads to the dynamical

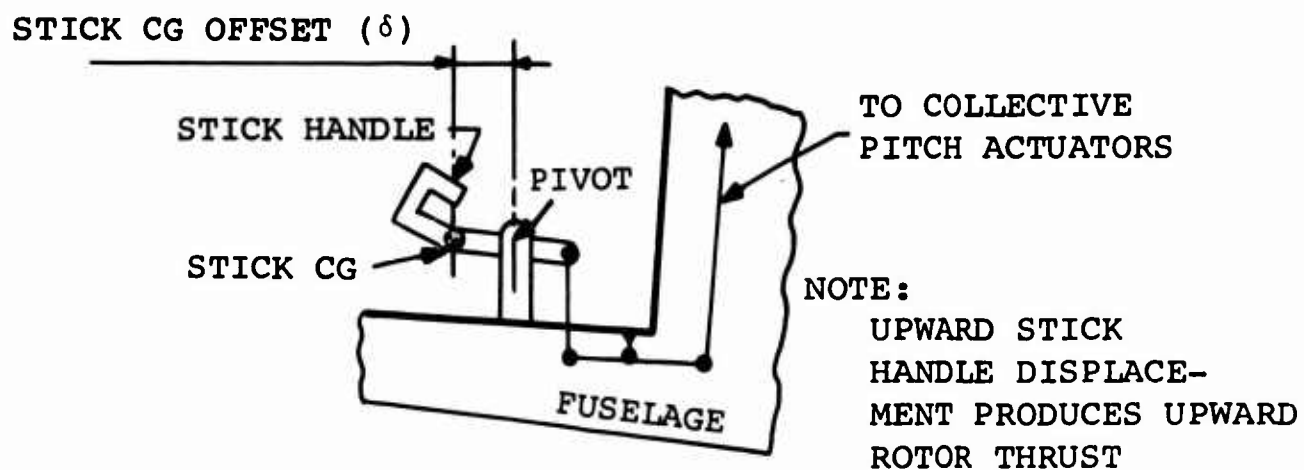


Figure 90. Collective Control Actuators Schematic

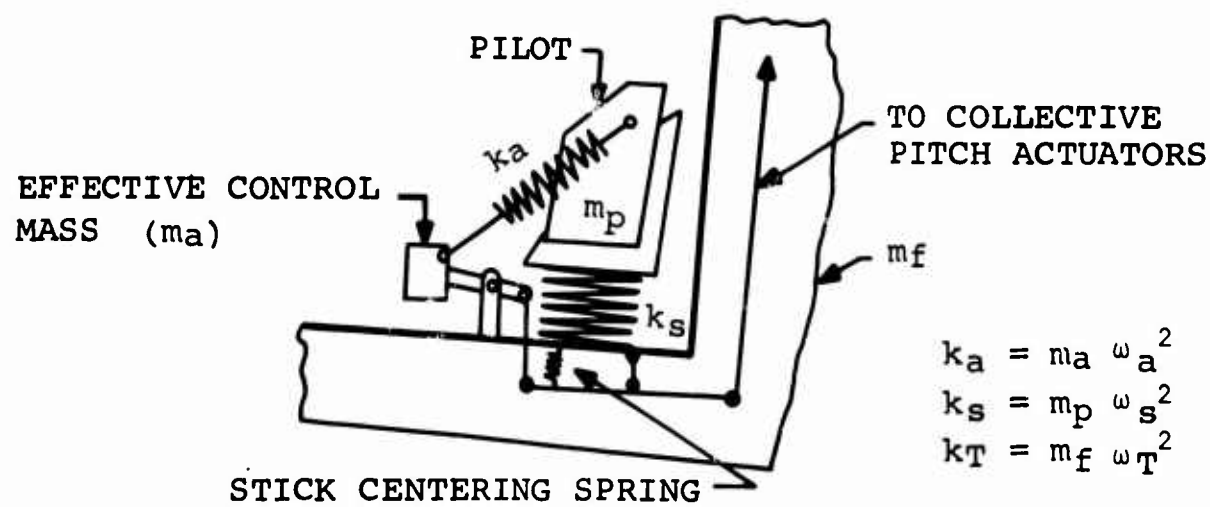


Figure 91. Simplified Model of the Destabilizing Pilot Control Feedback Loop

state in which a signal proportional to the vertical displacement of the helicopter is reproduced in exact form and is translated into the vertical force on the helicopter at a later time. Physically, this results in a delayed-action spring effect, the delay being measured by the magnitude τ .

Figure 93 is the root locus plot of the simulated delayed-action spring system in Figure 92. The system is neutrally stable when the gain (ω_T^2) is kept constant, for zero delay in the feedback ($\tau = 0$) and for $(\omega\tau) = \pi$. Instability results for any intermediate magnitude of the time delay, τ . The physical significance of this is as follows: at zero delay in the thrust feedback, the feedback mechanism provides the thrust directly opposing the helicopter displacement, while at $(\omega\tau) = \pi$ the feedback provides thrust in the direction of the displacement. If the relation (ω_T/ω_S) is less than 1.0 (i.e., if the feedback is not strong enough to overcome the natural stiffness of the system, k_S , continuously), the resulting motion will always be an oscillatory one. This oscillatory motion will be neutrally stable (i.e., will continuously oscillate when disturbed) at $\tau = 0$ and at $\tau = \pi/\omega$, or, equivalently, at zero and 180-degree phase shift between the helicopter displacement and the thrust feedback. It will be divergent for any intermediate phase relation, and the frequency of these divergent oscillations will be somewhere between $\omega_S \sqrt{1 + (\omega_S/\omega_S)^2}$ and $\omega_S \sqrt{1 - (\omega_T/\omega_S)^2}$, depending on the actual magnitude of the effective time delay, τ .

A somewhat more revealing picture of the destabilizing collective feedback is provided by a different interpretation of the mathematically equivalent system shown in Figure 94. The characteristic equation defining the stability of the system in Figure 92 does not change when the natural frequency of the system, ω_S^2 , is interpreted as the vertical g-sensitivity of the pilot's body and the pilot's seat combination (i.e., pilot vertical acceleration in g's per unit vertical displacement). At the lower frequency limit, given by

$$(\omega/\omega_S) = \sqrt{1 - (\omega_T/\omega_S)^2}, \quad (14)$$

the pilot moves with the fuselage, but the resulting thrust lags behind his vertical motions. The destabilizing mechanism is provided here by the pilot's inadvertent actuation of the collective control stick when the helicopter enters a vertical disturbance. The resulting oscillatory motion of the entire helicopter will be divergent, beginning at the oscillatory

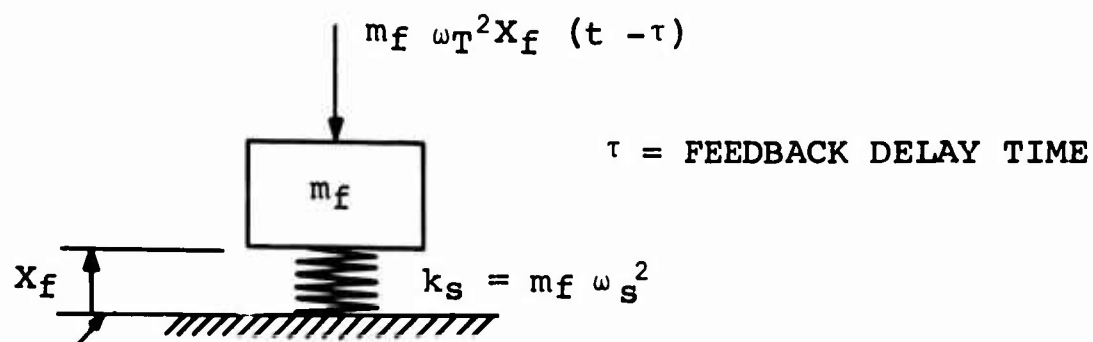


Figure 92. Displacement Feedback Loop Containing Time Delay

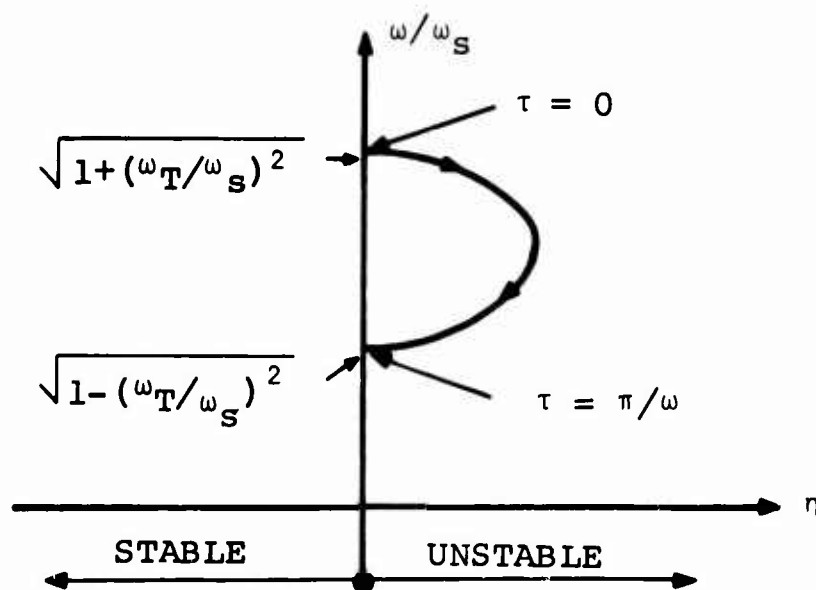


Figure 93. Root Locus Plot for Delayed Displacement Feedback with Constant Gain

frequency of the lower limit shown in Figure 93, and will continue to diverge as long as the pilot maintains himself in the control loop.

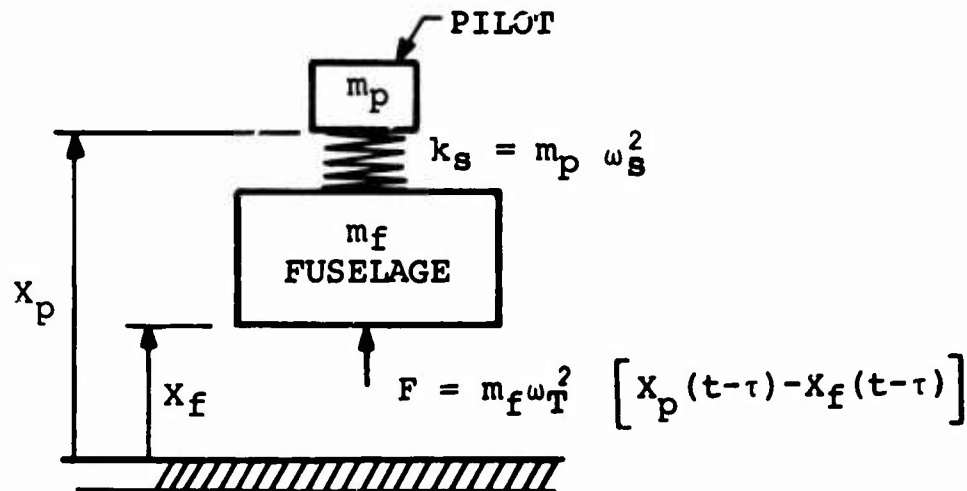


Figure 94. Pilot and Fuselage System Containing Delayed Displacement Feedback

Effects of Control System Parameters on the Unstable Vertical Bounce Without External Loads

Figure 90 shows a simplified model of the pilot collective control feedback loop which contains all the important parameters leading to collective bounce instability. This model was utilized to obtain the qualitative trends resulting from varying some of the collective control design parameters. The effect of the control system parameters shown in the following diagrams has been evaluated on a separate basis -- that is, only one parameter was studied in each diagram in order to determine its basic effects. An evaluation of the optimum control system parameter combination was not attempted in this study, although the existence of such a combination is possible.

The basic feature of the closed-loop collective control system shown in Figure 90 is the resulting dependence of the stability of the motion on the pilot's grip of the control stick, as shown in Figure 95, which gives the stability boundary of the system in terms of control stick sensitivity and relative

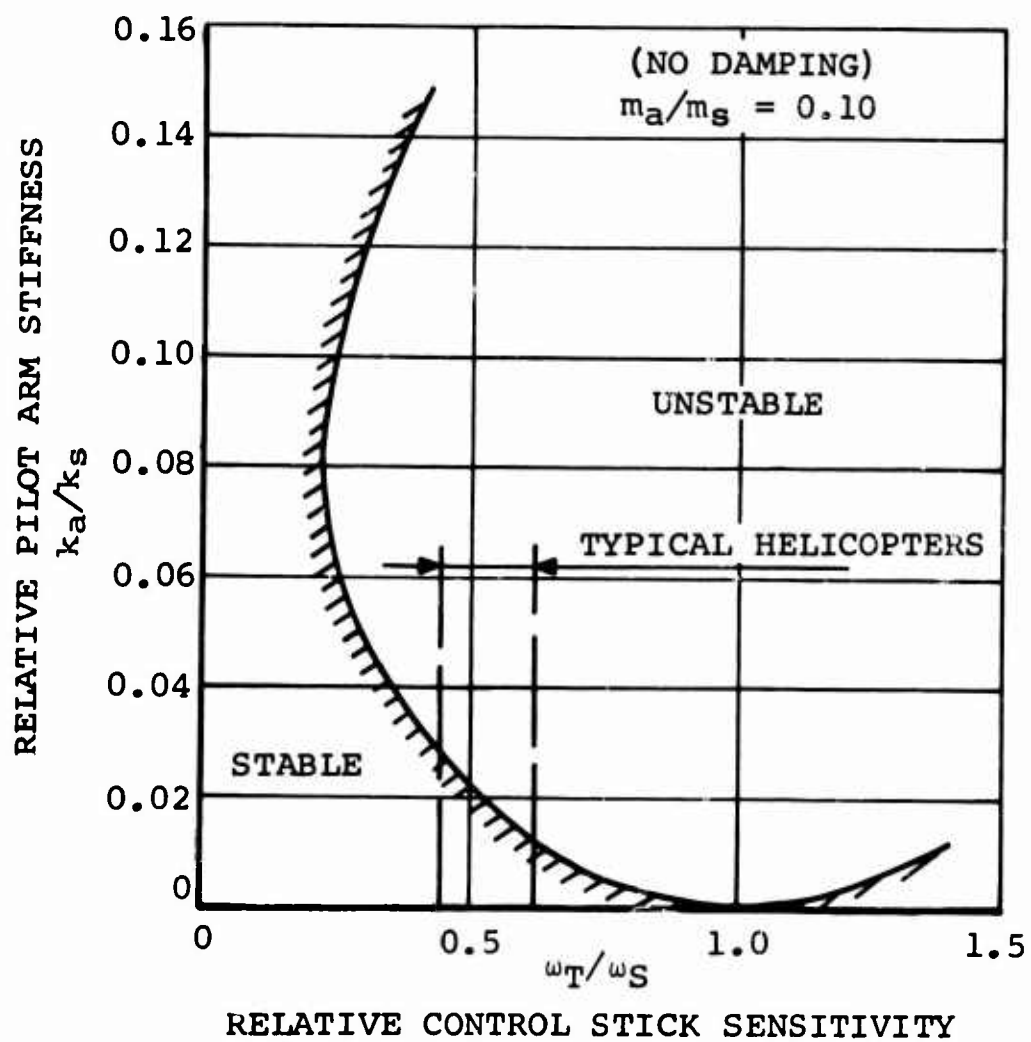


Figure 95. Vertical Bounce Instability Without External Load

pilot's presence in the control loop.

While this figure indicates that the pilot may make the system stable or unstable, depending on his loose or stiff grasp of the control stick grip, the flight test data indicate a more uniform behavior of the system. The conclusion to be drawn here is that the pilot's grasp of the control stick is most likely to be constant, somewhere in the unstable region.

The effects of the control stick sensitivity evident from Figure 95 indicate that typical collective control requirements will invariably place the aircraft within the unstable reach of the piloting technique. Some reduction in the maximum rate of divergence may be expected from lower stick sensitivities typical of present-day helicopters, as shown in Figure 96.

Complete stabilization by means of the high-rate linear dampers studied in Figure 97 does not appear practical, because the high damping rate requirements may possibly interfere with other control requirements during flight. Special nonlinear dampers may be effective if their damping characteristics sufficiently minimize inadvertent pilot actuation of the control stick in some specified frequency band, particularly in the range of small collective stick displacements. As far as this simplified analysis is concerned, the control damping affects principally the divergence rate, as indicated by Figure 97, and would manifest itself in improved pilot feel of the unstable aircraft following introduction of the high-rate linear dampers.

A positive control stick gradient indicates a reduction in the divergence characteristics, although no realistic stick gradients are indicated which could completely stabilize the system. As shown in Figure 98, too-high orders of magnitude of the positive stick gradient are needed to make the system completely stable.

The qualitative aspects of the friction lock effects and the collective bounce tendencies are illustrated in Figure 99. The friction lock is provided on the collective stick grip on most of the helicopters in order to enable the pilot to adjust the control feel to his particular preference. Essentially, it provides a positive resisting force of sufficient magnitude to hold the collective control setting in any position. As such, it provides a locking device which allows the pilot to hold the collective stick in the desired position with the

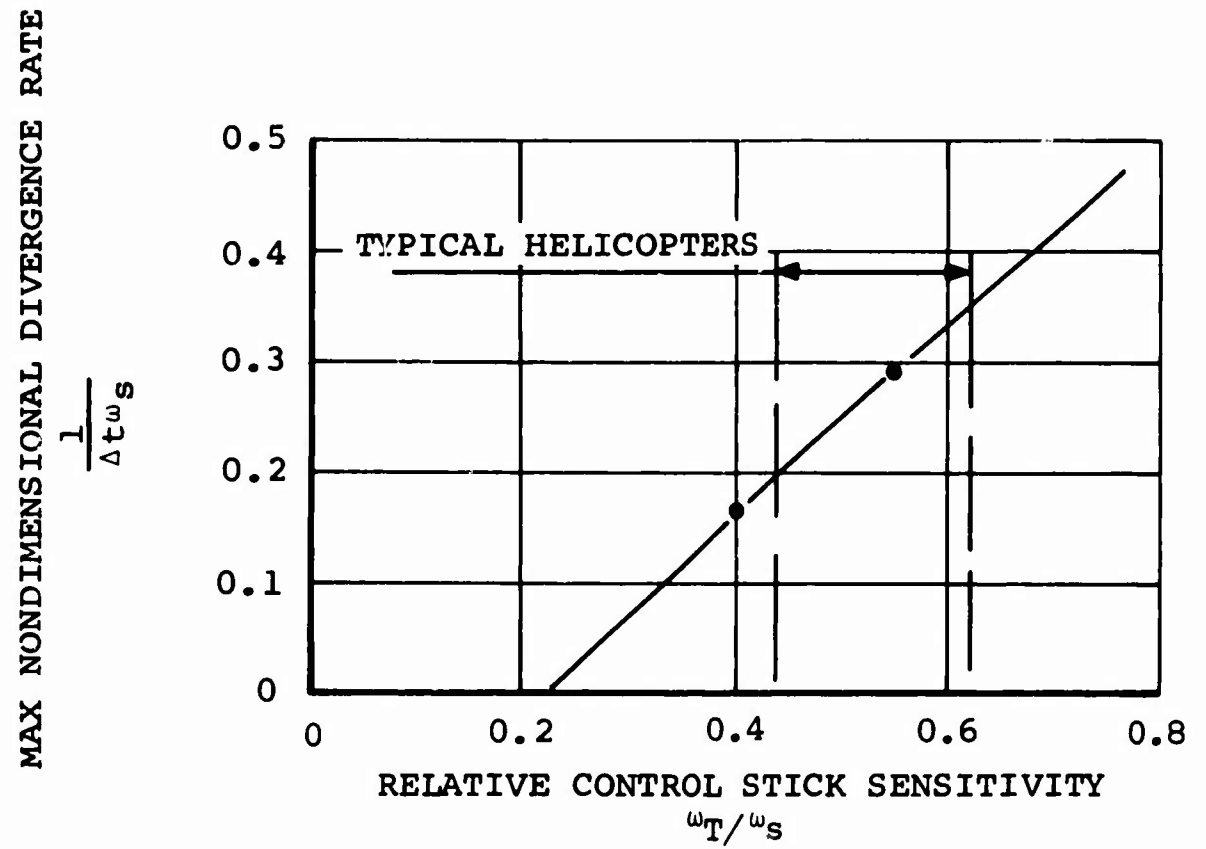


Figure 96. Effect of Stick Sensitivity on Divergence Rate

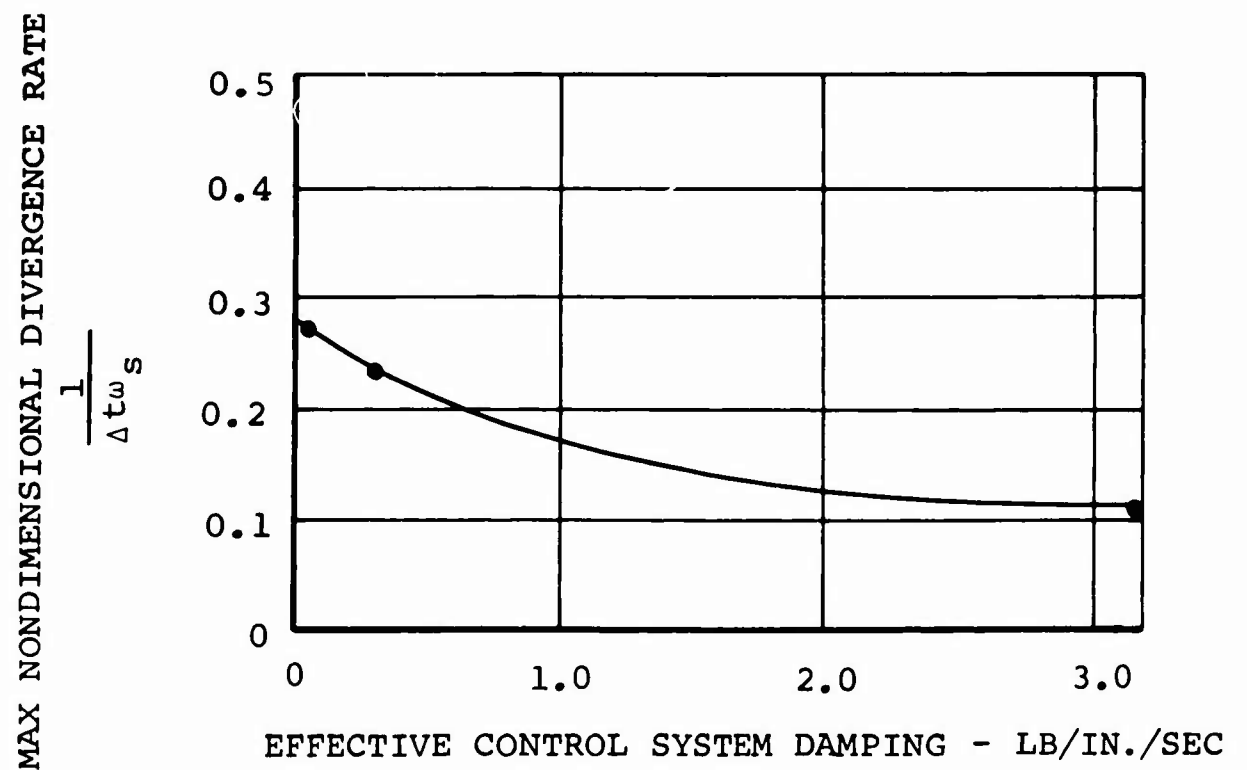


Figure 97. Effect of Control Damping on Divergence Rate

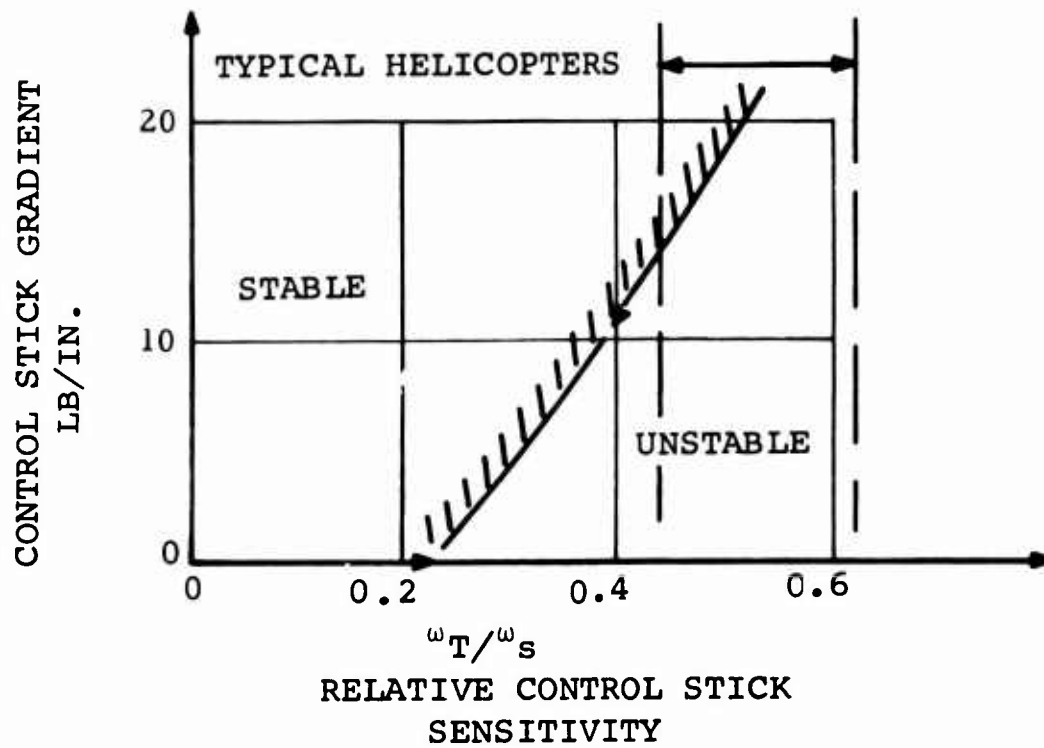


Figure 98. Effect of Control Stick Gradient

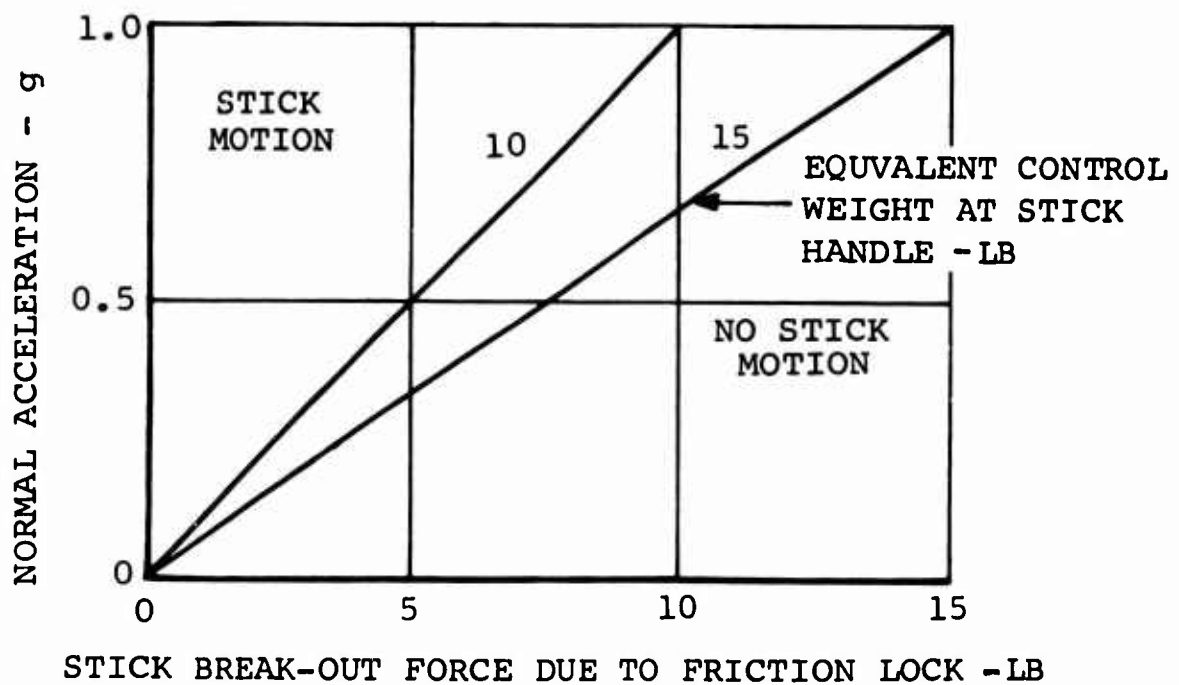


Figure 99. Stabilization Through Friction Lock Devices

desired rigidity. With regard to the application of friction devices to the stabilization of vertical bouncing tendencies, the main effect here appears to be in the positive locking quality provided. If the break-out force required to move the stick is sufficiently high, the inadvertent pilot action on the stick will not displace the stick from the fixed setting. Figure 99 simply points out the minimum acceleration levels which would be required at least to offset the friction locking force for a 10-15-pound effective unbalanced control weight (including any pilot hand effects). At the 10- and 15-pound lines shown here, the collective stick will experience a sufficient acceleration level to neutralize the locking force. In order to result in instability, the oscillatory disturbance level will have to exceed this breakaway force during most of the motion; the instability would then occur somewhere above the equilibrium lines shown. In any case, the illustration is sufficient to indicate that small amounts of friction - say, 5 pounds - may result in stable behavior unless the oscillatory disturbance level significantly exceeds 0.5g.

Unstable Vertical Bounce with External Load

Previous discussions have indicated that the vertical helicopter motions are essentially stable unless a collective control feedback loop is effectively closed by the pilot. The stability of the system without the collective feedback, but with the load, follows from the stability considerations of the linear time-independent systems. These considerations simply indicate that a system with natural spring, mass, and damping characteristics cannot become unstable through a mechanical spring coupling of an additional mass, unless the original system was already unstable. These aspects of the linear system lead directly to the conclusion that the unloaded helicopter must be inherently susceptible to the divergent vertical oscillations, if it becomes unstable through the addition of an external sling load. It becomes, then, necessary to include the unstable collective control feedback in any realistic study of the divergent vertical oscillations in sling-loaded helicopters. The following discussion is based on the unstable collective feedback loop discussed previously but with the coupling effects of the external sling load added.

Figure 100 illustrates the effect of the external sling load frequency on the behavior of the combined system at a relatively low collective stick sensitivity and with no control system damping. It is seen that within the pilot control

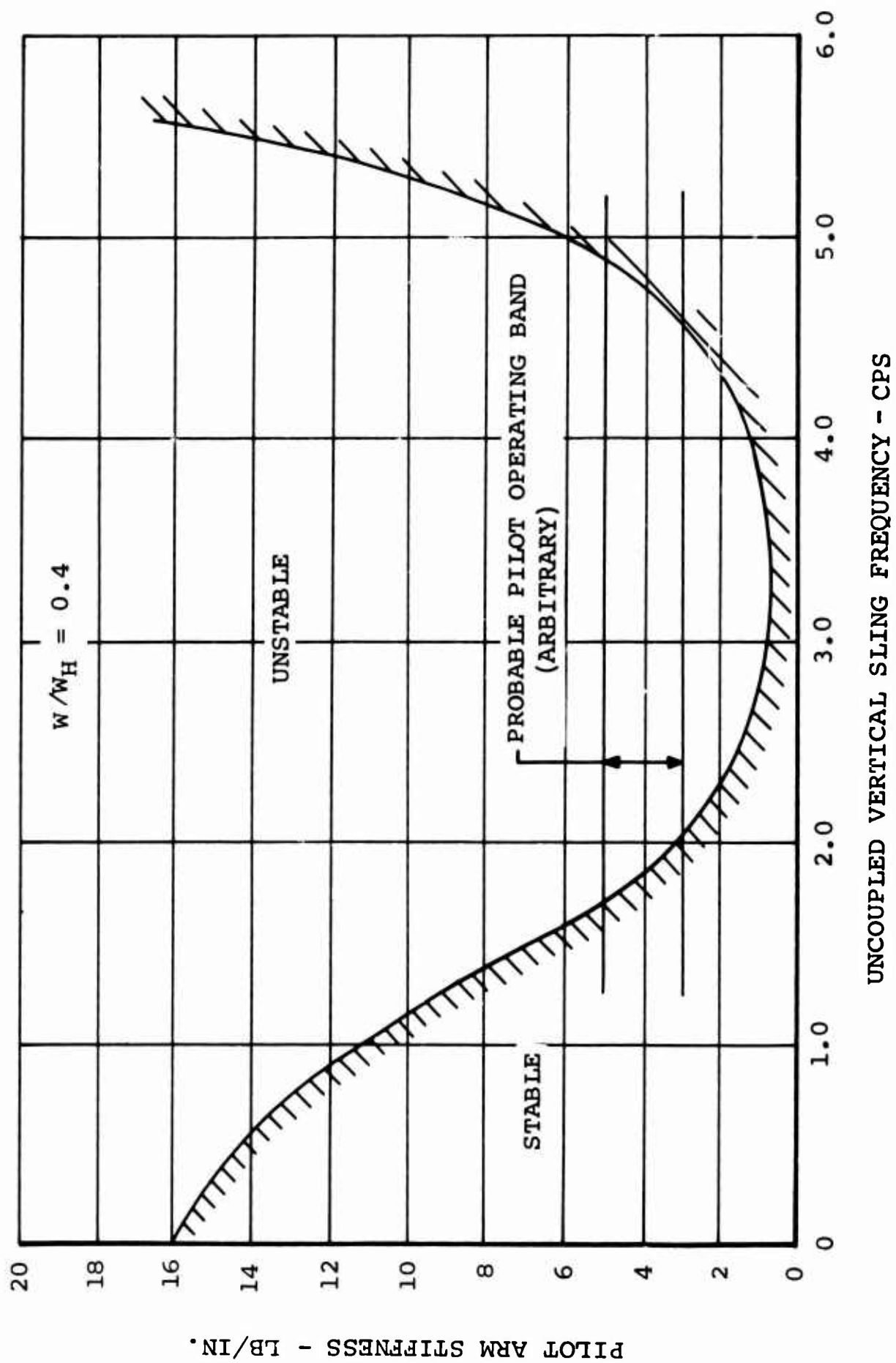


Figure 100. Vertical Bounce with External Sling Load

operating region, a stable no-load configuration may become unstable at an external sling load frequency of about 2 cycles per second and remain unstable unless the sling load frequency is held below the 2-cycles-per-second level or is higher than about 5 cycles per second. It is interesting to note that the low-frequency margin, which is rather narrow, is exactly the operating region of the nylon slings. It suggests that a load isolator with an operating frequency of 2 cycles per second may effectively place the operational behavior of the helicopter in the stable region, since any of the sling loads in series with the isolator would reduce the effective frequency below the 2-cycles-per-second level.

Figure 101 shows the vertical frequency distribution for a typical single-point suspension system utilizing steel and nylon cables. The lower boundary of each of the cable systems corresponds closely to the frequency obtainable with the most efficient utilization of the sling, i.e., carrying loads which result in the maximum allowable load on the cable. The upper boundaries are only approximate probabilities, since no theoretical limit may be placed on the inefficient use of the slings. Figure 101 clearly indicates that the wide distribution of the approximate operating regions makes it impractical, if not impossible, to avoid the instability merely by the choice of appropriate slings. The possibility of inefficient sling utilization (i.e., using sling combinations with rated capacities greatly in excess of actual weights being carried) will invariably lead to a particular sling configuration highly susceptible to divergent vertical oscillations.

Figure 102 indicates the modification of the vertical frequency distribution resulting from the use of multiple legs with a spread of 20 feet. Even with such large spread distances, significant advantage may be obtained for the length-spread ratios of less than 0.5 (i.e., with the slings inclined at 45 degrees or more). No significant improvements in the overall vertical bounce stability characteristics may then be expected from the various sling configurations, although the use of nylon slings reduces the overall probability of obtaining an unstable sling configuration within the entire operational envelope.

Elimination of the Collective Bounce Instability

The basic mechanism of the collective bounce instability (in which the collective control feedback loop is effectively

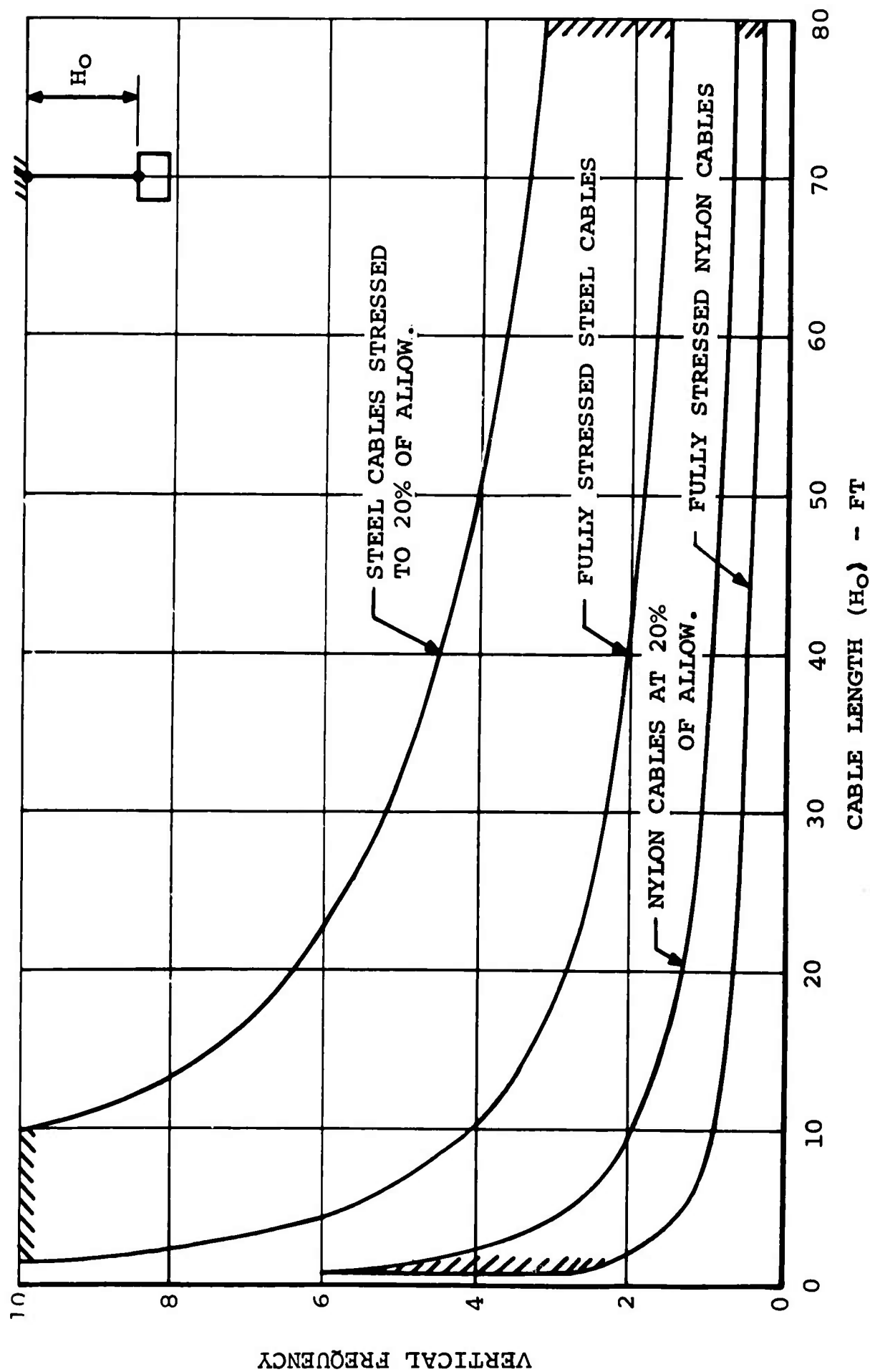


Figure 101. Vertical Frequency Distribution for Single-Cable Suspensions

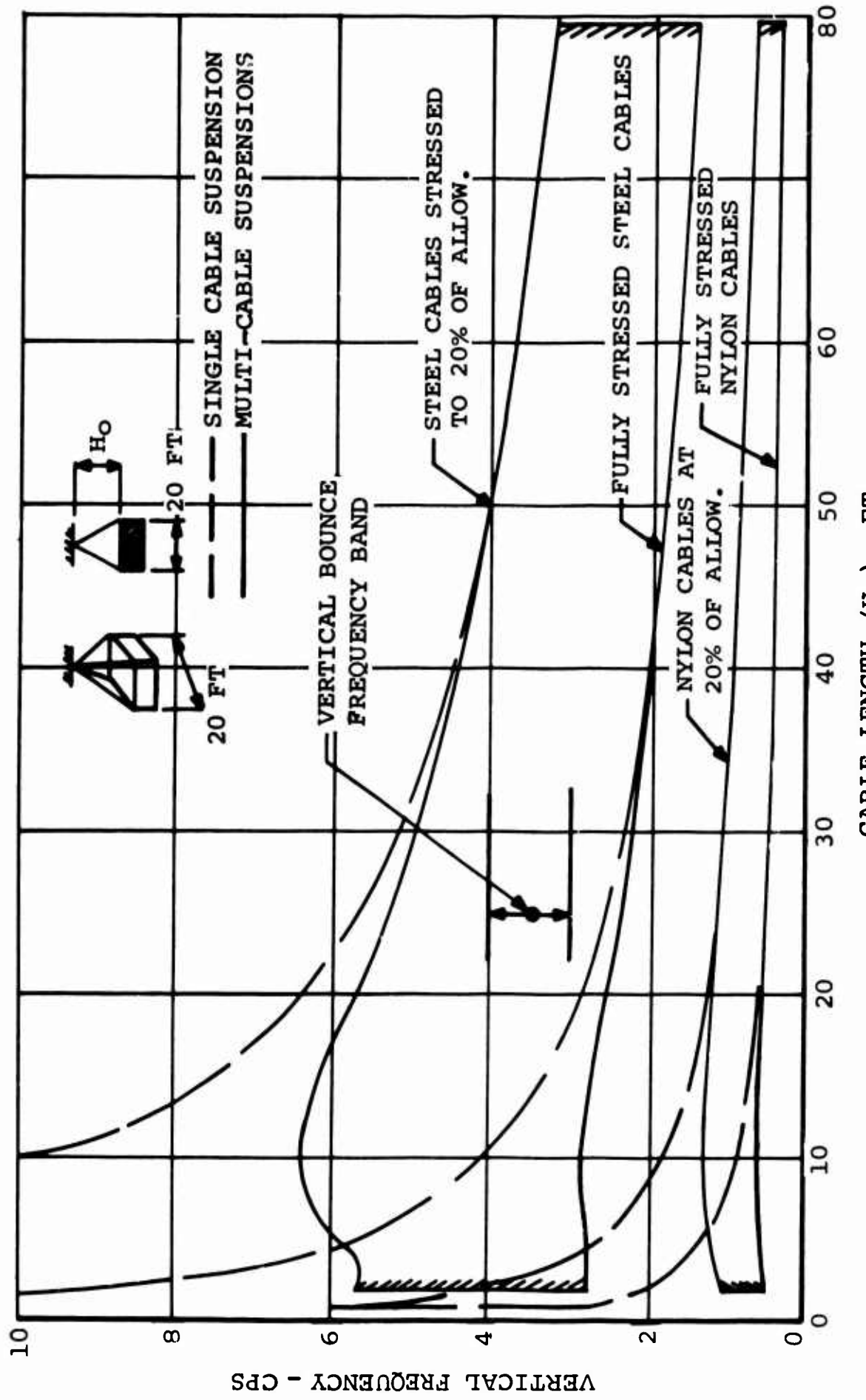


Figure 102. Vertical Frequency Distribution for Single-Cable and Multi-Cable Suspensions

closed by the pilot when he grasps the control stick grip and releases the locking mechanism) offers several suggestions for the elimination of this instability, as described below:

1. Design of Control Actuators - The design criterion to be followed here is the uncoupling of inadvertent vertical pilot motions from the control actuators, to ensure that if the pilot's body is disturbed by the transient vertical helicopter oscillations, his resulting motion does not disturb the control actuators. This leads to the concept of providing horizontal control actuator motion in order to produce vertical control forces.
2. Stick Position Locking Devices - A positive locking device on the control actuator which acts at all times and demands forceful actions from the pilot in order to displace the controls is conducive to stability. While these devices may still lead to instability under sufficiently high disturbance, the flight test data suggest that the resulting divergence rate may be considerably reduced (by as much as a factor of 2). An additional desirable feature of such locking devices would be a positive lock to enable the pilot to hold the stick in a rigid position with respect to the fuselage when he has to control the divergent vertical oscillations. The magnetic brake provided on some helicopters has this desirable feature.

It should be noted at this point that all attempts to stabilize the divergent vertical oscillations lead to the effective prevention, or at least minimization, of the collective stick feedback through the pilot's body motions, particularly in the region of small-amplitude oscillations of less than 0.5g, which may easily start when the heavy external load is disturbed. The experience gained to date in operational and experimental flights clearly demonstrates that this feedback should be eliminated by means of stick control designs in which such oscillatory feedback does not occur -- at least in the incipient stage, if not throughout the entire possible range of the divergent oscillatory level. If these divergent oscillations are encountered during actual flights with the existing aircraft configuration, the pilot must take all steps to lock the control stick positively and to keep himself out of the collective control loop until the oscillations die out.

Successful completions of external cargo-carrying missions with particularly sensitive systems are still possible if the collective control is applied incrementally and the pilot removes himself from the control loop whenever the oscillations appear. Further application of the collective control in this incremental fashion should follow, when the pilot has sensed that the oscillations have decreased to a level consistent with his control confidence.

AIRFRAME VIBRATION

Fuselage Response with Slung Cargo Loads

Levels of aircraft vibration are established by (1) the dynamic characteristics of the fuselage-cargo and (2) the vibratory load excitation. Slung cargo loads significantly change the fuselage dynamic system because basic aircraft modes of rigidity and flexibility are coupled to the cargo with additional degrees of freedom. Vibratory loads exciting the fuselage-cargo system consist of the blade root vibratory loads transmitted to the fixed system and the aerodynamic load generated by the sling and cargo.

Fuselage-cargo dynamics may be divided into two separate investigations, each of which can be fully analyzed independently. The first, and the essential, study of fuselage-cargo dynamics consists of the two-degree-of-freedom system of a cargo mass attached by a flexible sling to a rigid fuselage. Investigation of the degrees of freedom of a slung mass is presented at the beginning of this section. It is noteworthy that the operational restrictions in using a cargo sling generally result from excitation of the rigid fuselage-cargo system. The second study area of fuselage-cargo dynamics comprises investigation of fuselage response to vibratory loads generated by the rotor system. Since the vertical vibration levels correspond to the rotor blade number harmonics, the second study is limited to the 3Ω (where Ω is one rotor revolution) vibration levels.

Present investigation is limited to the vertical-longitudinal response of the fuselage. Lateral-torsion representation of the fuselage, using engineering beam theory for comparison testing, was found to be inadequate. Since favorable beam theory testing is a prerequisite for the response analysis, computations with the lateral-torsion simulation would be meaningless. Idealization of the fuselage for the vertical

solution considered 18 mass stations. The stations were connected to each other by elastic beam elements and to a suspended cargo mass, as shown in Figure 103. Aircraft gross weights were 27,570 pounds and 34,770 pounds, corresponding to cargo loads of 4800 pounds and 12,000 pounds, respectively. For each gross weight configuration, rotor vibratory loads were predicted from the aeroelastic rotor analysis, D-94, obtained at speeds of 80 and 100 knots. CH-47A production blade properties were used in the blade mathematical model. It is noteworthy that measured vibratory loads are not available for the CH-47A.

Two assumptions were made for the prediction of rotor loads: (1) that hub motion has no effect on vibratory rotor loads, and (2) that aircraft trim changes only with total aircraft weight and airspeed. These assumptions appear reasonable for a preliminary response study.

Vertical vibration levels for the cockpit and midcabin were computed at two airspeeds, since cargo loads of 4800 pounds and 12,000 pounds were considered. A vibration level for each condition was determined as a function of the cargo mounting frequency, and then compared with the vibration of a comparable internal cargo and that of an empty aircraft.

Figure 104 presents the calculated vertical vibration levels for a 4800-pound slung cargo load. For both cabin and cockpit, predictions show the vertical vibration level increasing as the cargo/sling-mounting-system frequency is increased. In the range from 2 to 6 cycles per second, cockpit vibration increases 20 percent and midcabin vibration over 50 percent. Measured data for internal cargo are shown and compared to the calculated response of the fuselage with a slung load. Comparison shows good agreement for the cockpit but poor agreement for the midcabin.

Vibration levels for the 12,000-pound slung cargo load are shown in Figure 105. In the vicinity of a cargo/sling-mounting-system frequency of 1.5 cycles per second, predicted vibration levels are comparable to the lower weight cargo configuration. Cockpit vibration trends with mounting frequency are nearly identical to those for the 4800-pound cargo load. At 100 knots, midcabin vibration increases more rapidly with increasing slung cargo weight. At 80 knots, the vibration level increase is apparent only to 3.5 cycles per second; above 80 knots a leveling trend is noted. Measured data comparisons

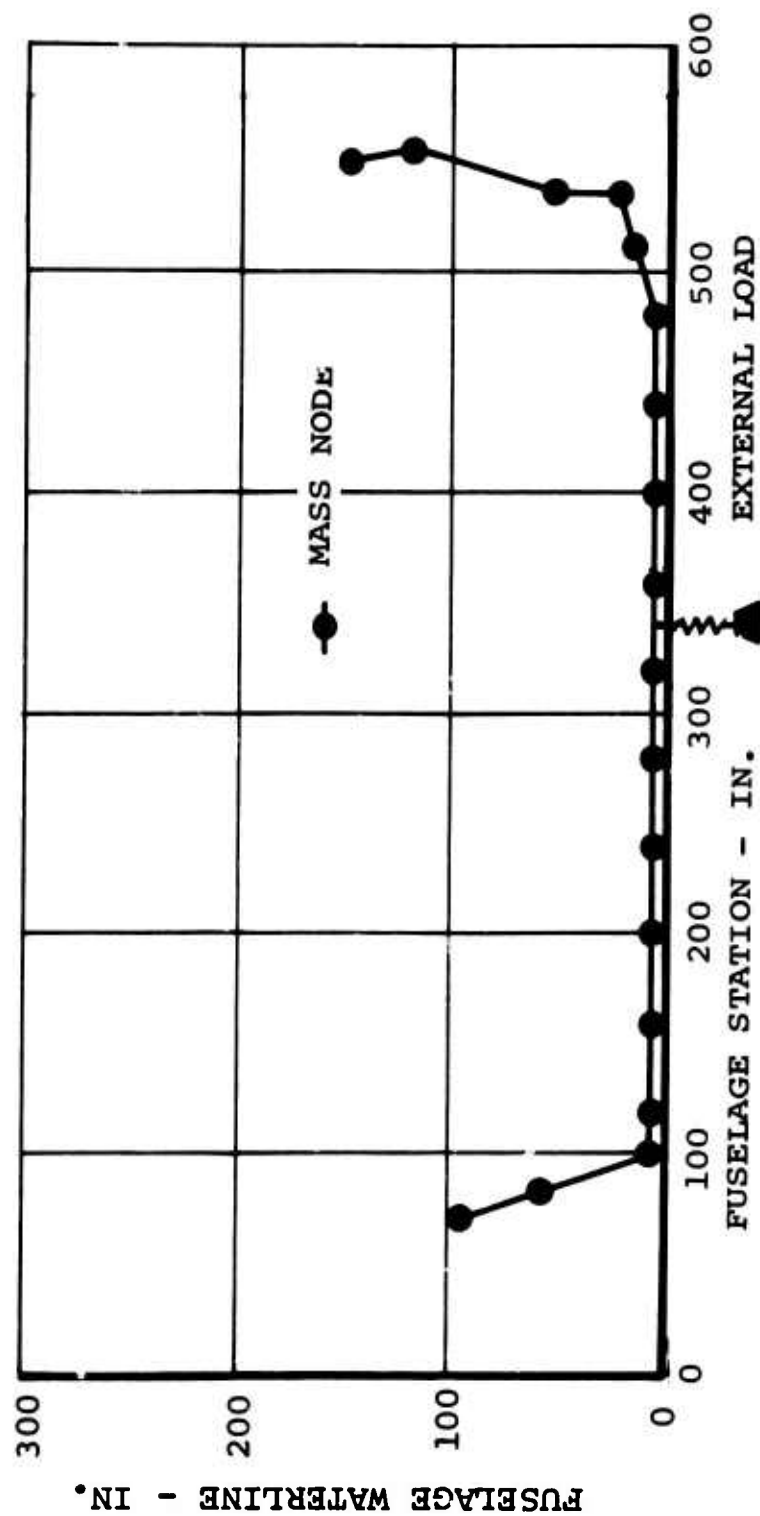
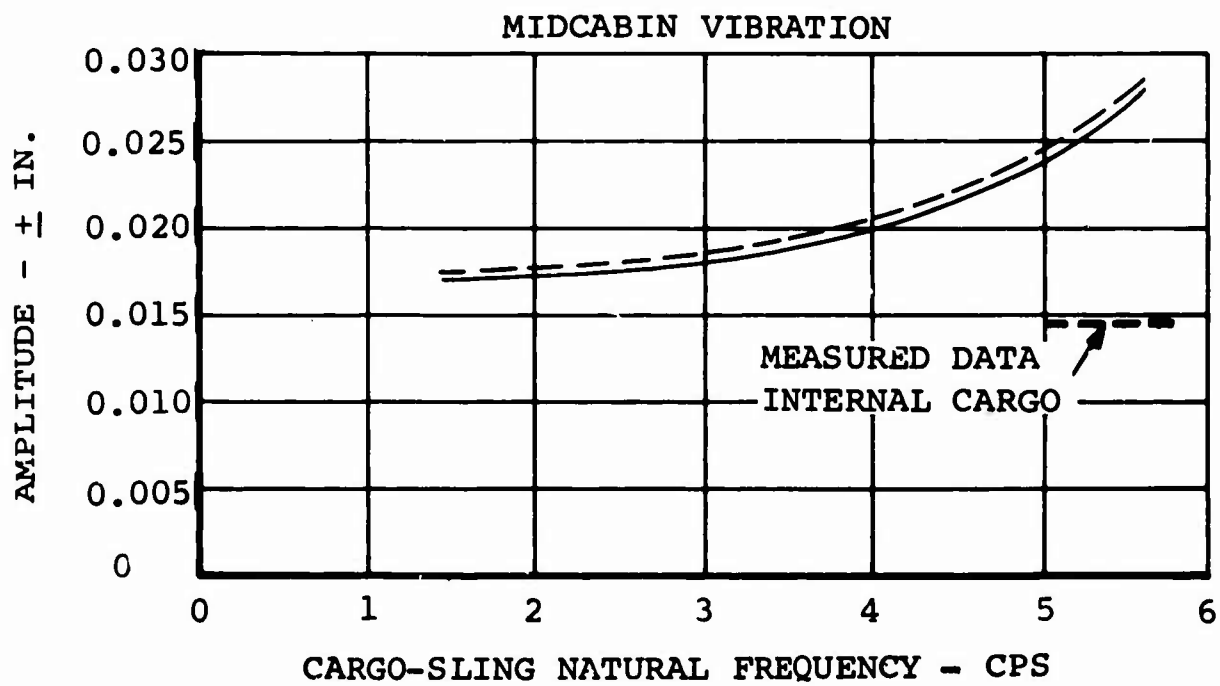
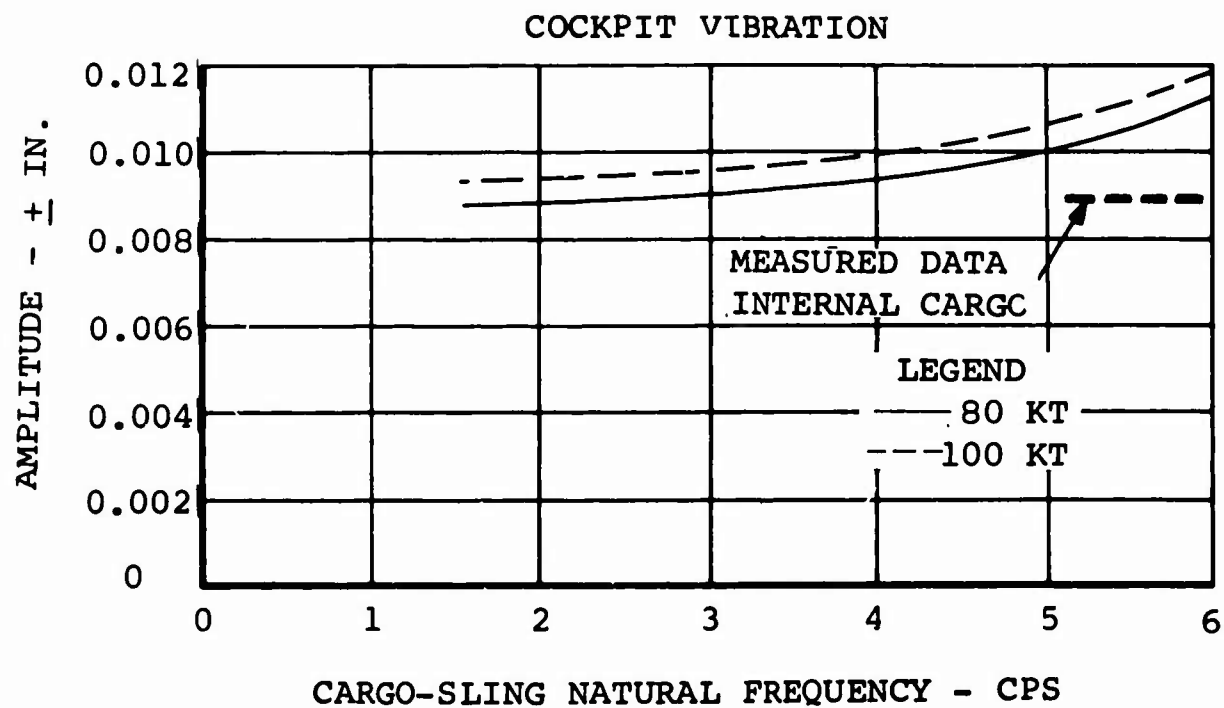
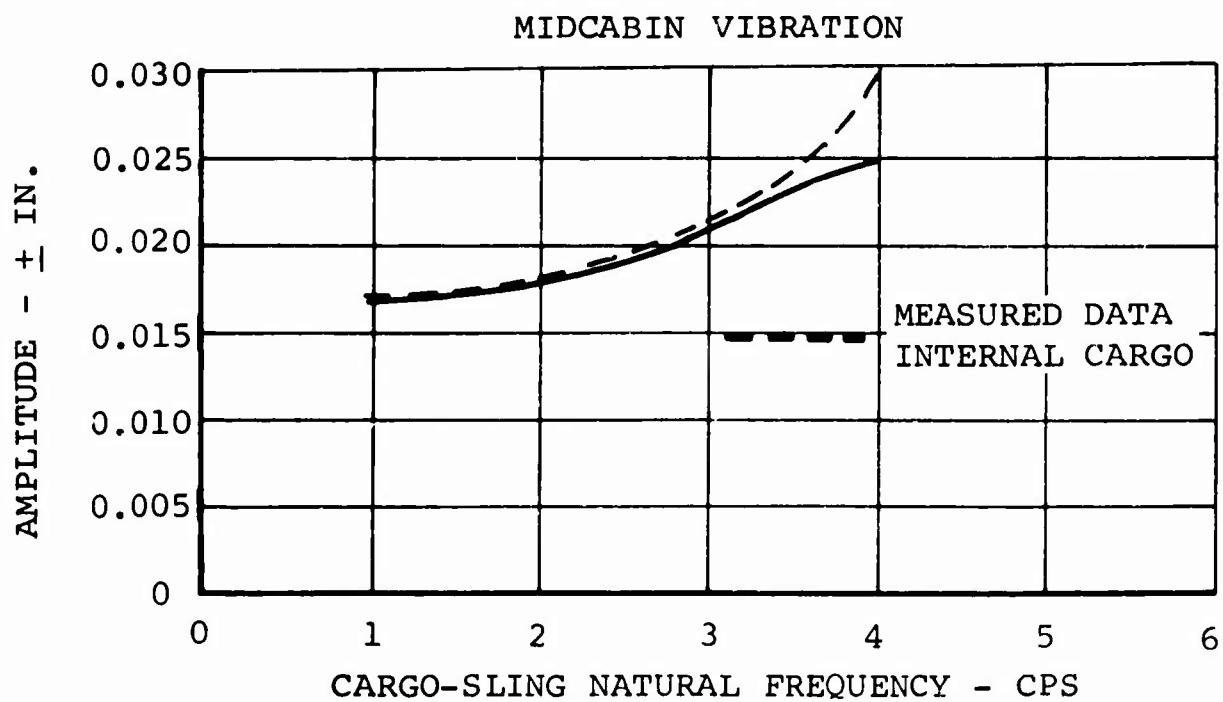
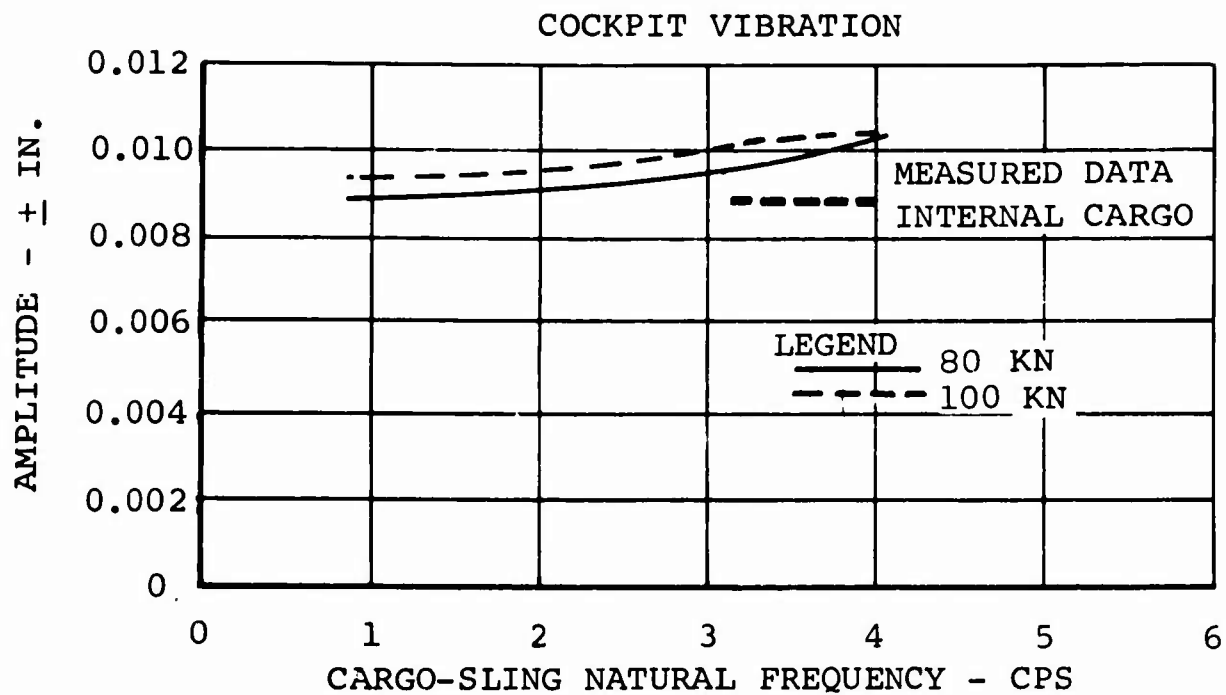


Figure 103. CH-47 Vibration Analysis, Lumped
Mass Fuselage Idealization



GW - 27,570 LB
 Ω - 230 RPM

Figure 104. CH-47 3/Rev Vibration - 4800-Pound External Load



GW - 34,774 LB
 Ω - 230 RPM

Figure 105. CH-47 3/Rev Vibration - 12,000-Pound External Load

are similar to those for the 4800-pound configuration, which exhibits good vibration level agreement in the cockpit and poor agreement in the cabin.

Preliminary study has shown that 3 Ω vertical vibration of a CH-47A can be minimized within a 1.5-cycles-per-second vibration area. Both 4800-pound and 12,000-pound slung cargo loads were lifted using a soft sling mounting.

Cockpit vibration levels are insensitive to the mounting frequency. Vibration levels at midcabin can be increased by over 50 percent by increasing suspension frequency in the range between 1.5 and 5.5 cycles per second for the 4800-pound slung load, and between 1.5 and 4.0 cycles per second for the 12,000-pound load.

STABILITY IN HOVER AND FORWARD FLIGHT

The numerical evaluation of helicopter stability characteristics involves determination of the trim attitude for a desired level flight or a sustained maneuver. The particular trim requirements determine the disturbance gradients, which, in general, will depend on the helicopter configuration and fuselage aerodynamic characteristics. These disturbance gradients represent the changes in transient forces on the helicopter brought about by the unit change in helicopter trim attitude and velocities. The stability, as such, indicates whether the helicopter will return to the original flight condition when disturbed by sudden external forces, or will enter another, possibly dangerous, flight condition. A dynamically stable helicopter will return to the original flight attitude following a sudden disturbance of finite duration. An unstable one will generally require pilot control inputs in order to return to the desired flight conditions. From the viewpoint of the pilot's handling requirements, a stable helicopter is desirable for any sustained flight condition to avoid burdening the pilot with a continuous control application. An instability in the aircraft may still be tolerable if it is slowly divergent and oscillatory. The oscillatory character is desirable here because it gives the pilot a warning that something is happening and enables him to sense the rate of divergence. If the divergence is sufficiently slow, the pilot has sufficient time to apply corrective measures through his controls.

The basic helicopter system has two important modes of dynamic instability, the longitudinal and the lateral directional. The longitudinal mode consists of the coupled pitch, longitudinal, and vertical motions. It may be a slow oscillatory divergent mode or a pure divergent motion, depending on the rotor configuration. In hover this mode is marginally unstable; it deteriorates rapidly with increased forward speed. This is generally attributed to increased angle-of-attack instability with forward speed, in which the aerodynamic pitch moment on the fuselage is directly proportional to the aircraft pitch attitude with respect to the flight path; it tends to rotate the aircraft in the direction of the increasing pitch attitude, thus further increasing the pitch moment.

The lateral directional mode is a coupled roll-sideslip (lateral motion) and yaw motion, generally of a slow oscillatory character and mildly divergent. The yaw motion here becomes more important in forward flight, because of the aerodynamics of elongated bodies, such as the typical helicopter fuselage. In hover the yaw motion is almost uncoupled, and the helicopter exhibits what is generally known as "Dutch roll", a pure roll and sideslip oscillation. In forward flight this mode is sometimes termed "yaw hunting", when the yaw motion becomes significant.

The long period and slow divergence rate of these two unstable modes in any helicopter enable the pilot to control the aircraft at slow and moderate forward speeds (less than 80 knots), without considerable difficulties, through a continuous and coordinated application of the controls. At high forward speeds this pilot control loop becomes too tight and tiresome for the pilot, and automatic stability augmentation devices are utilized to alleviate the continuous burden on the pilot. For good handling qualities at high forward speeds, a slow, oscillatory convergence, or non-oscillatory convergence, becomes a requirement.

The suspension geometries that have been investigated with respect to helicopter dynamic stability are shown in Figure 106. The basic feature of these geometries is the independent attachment of each cable, both at the helicopter and the load. Three main configurations were investigated: a single-cable attachment, a twin-cable attachment along the longitudinal axis with parallel or inclined cables, and a four-parallel-cable suspension. In all cases the load cg position was located on a common vertical passing through the helicopter cg.

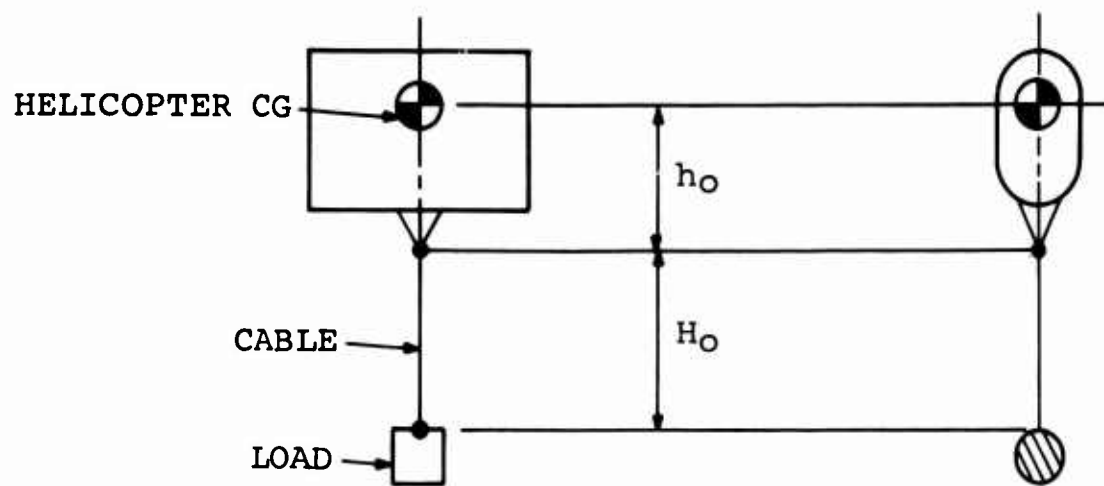
This configuration is consistent with the trim equilibrium position of the load when the aerodynamics of the load are ignored.

Hovering Stability

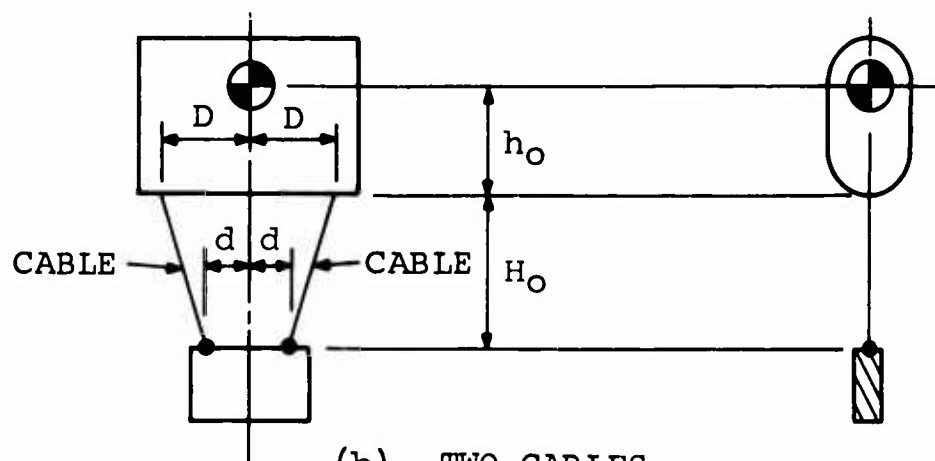
The dynamic response of the hovering helicopter has been investigated with respect to the basic geometries shown in Figure 106. The effects of (1) the location of the helicopter attachment point below the cg (dimension h_0), (2) the cable length (dimension H_0), and (3) the relative spread in the turn-cable suspension, as expressed by the ratio of the distances d/D , have been investigated in terms of the relative load-to-helicopter weight ratio, pitching-moment-of-inertia ratio, and cable stiffness. The relative weight ratios considered were 0.5 and 1.0, and the relative inertias were 0.04 and 0.90. Nylon and steel cables were considered in the definition of the cable stiffness.

The results of analytical investigations show three parameters to be important in the determination of the overall dynamic response of the helicopter about its hovering position. The location of the cable attachment point below the helicopter cg appears to be the most influential, as shown in Figure 107. For good dynamic characteristic, this distance (h_0 in Figure 106) should be very small (less than 5 feet) either for single- or multi-point suspension. The length of the cables appears more significant if the cable attachment point is too far (more than 5 feet) below the helicopter cg and if the relative weight ratio approaches unity (i.e., if the helicopter carries dense weights equal to its own weight). In general, helicopter dynamic response may be expected to deteriorate somewhat when 80-foot, or longer, cables are used to carry heavy loads. The best overall configuration for heavy load missions appears to be the one with short cables (about 40 feet or less) attached to the helicopter less than 5 feet below the cg location. These results are true either for single- or multi-cable suspensions.

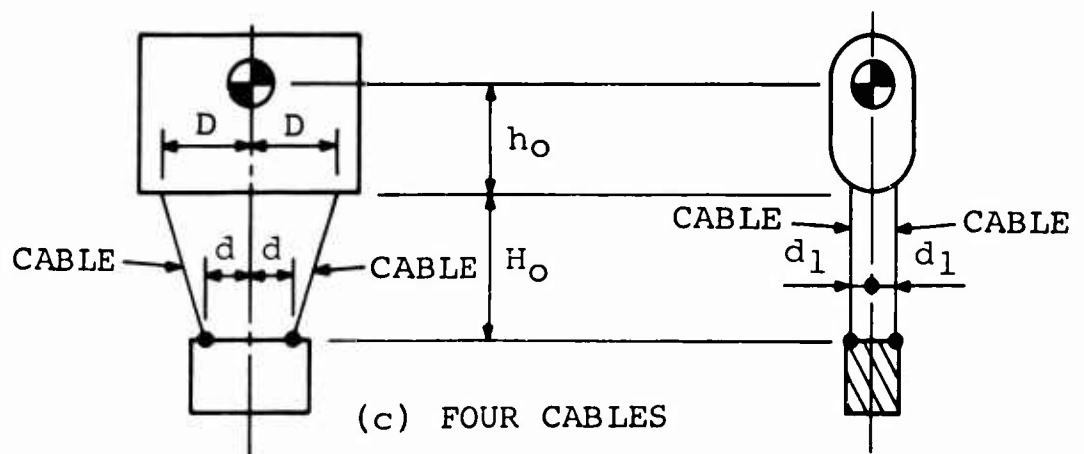
Investigation of the other geometrical parameters, such as relative cable spread or cable stiffness (nylon versus steel), reveals no significant deviation from the behavior defined by the distances h_0 and H_0 and the relative load-to-helicopter pitch or roll inertia. This parameter exhibits a destabilizing influence similar to the relative weight ratio.



(a) SINGLE CABLE



(b) TWO CABLES



(c) FOUR CABLES

Figure 106. Basic Suspension Geometries

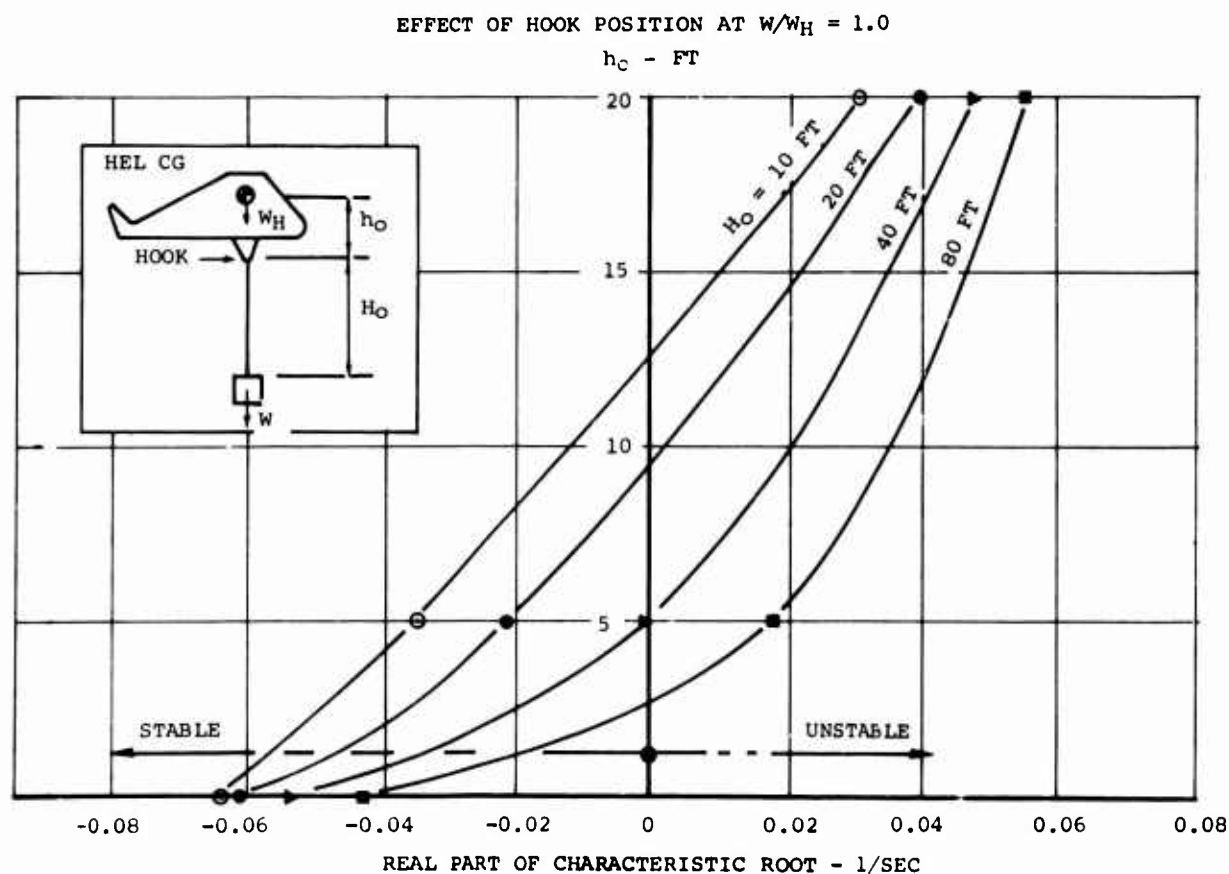
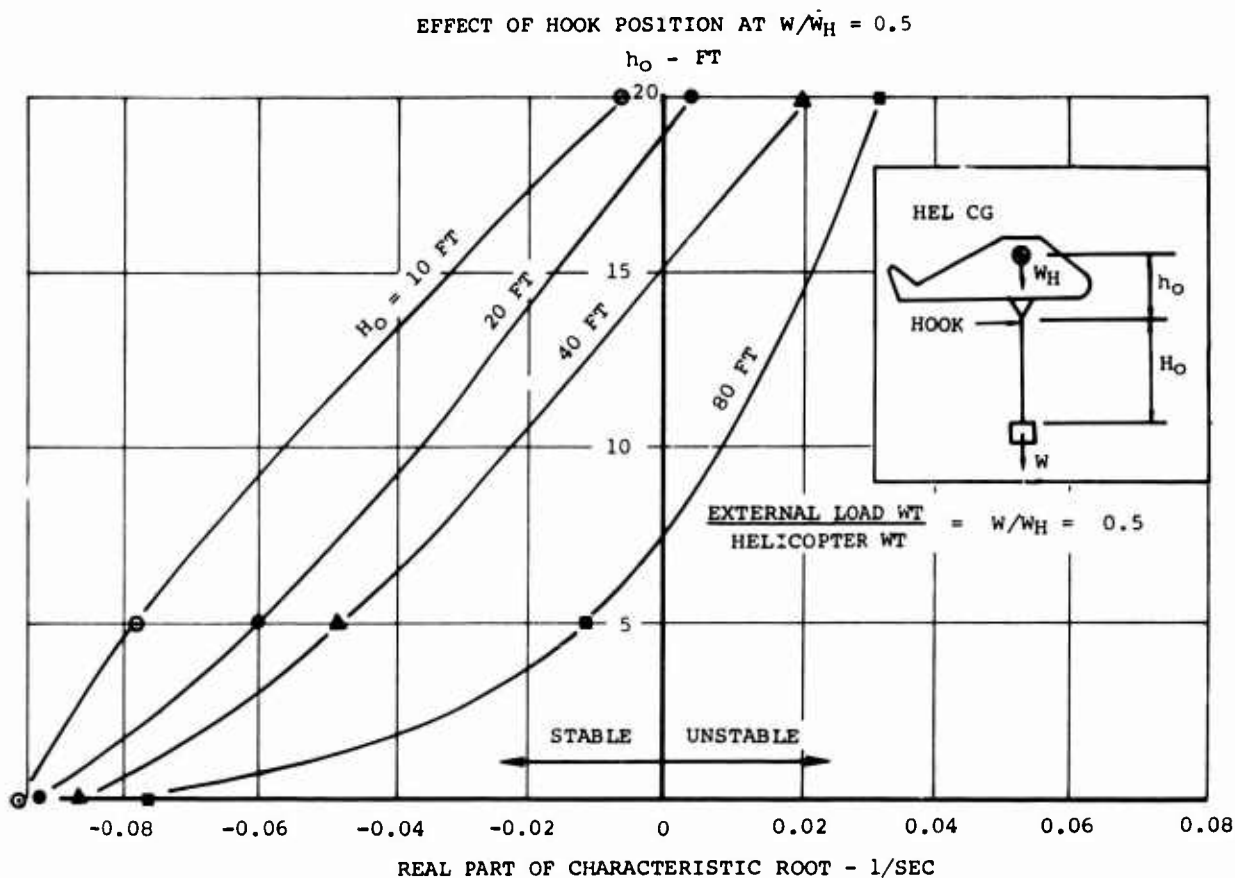


Figure 107. Effect of Distance Between CG and Suspension Attachment on Hover Stability

The general results of this investigation reveal that the dynamic response of the hovering helicopter utilizing the three basic suspension geometries shown in Figure 106 is similar to the single-cable configuration with the comparable basic distance parameters, h_0 and H_0 , and the relative weight and inertia ratios. This result is an outgrowth of the basic similarity in the coupling between helicopter and load when the governing mode is a pendular motion of the combined system suspended in space. In the entire span of the parameters studied, this pendular motion leads to instabilities which are very mild; they are of long-period duration and diverge slowly. No serious limitations on the hovering capabilities should arise, except possibly when the suggested boundaries are exceeded by a significant margin and a precise hovering capability above a point on the ground is required.

Forward Flight Stability

The flying qualities of the helicopter with an external load are primarily governed by the load aerodynamics. Reference 1, which presents the results of the aircraft recovery missions with small loads (i.e., relative weight ratios of one-third or less), indicates the necessity of loads' being aerodynamically stable for the successful completion of external cargo-carrying missions. In practice, dense loads with centrally symmetrical shapes exhibit marginal aerodynamic stability, unless special precautions are taken to ensure stability. Because the range of these stability characteristics is wide, the investigation carried out here assumed aerodynamically neutral stability of the external loads. If the full speed capability of the typical prime mover is to be utilized in carrying large odd-shaped loads, aerodynamic load stability must be artificially ensured by special aerodynamic surfaces.

A typical tandem-rotor helicopter configuration of current-production medium-transport type has been utilized to investigate the dynamic stability characteristics at a fixed load-to-helicopter weight ratio of 0.6. This ratio has been selected for two principal reasons: first, a realistic stability study should be based on relatively well-defined aerodynamic characteristics of the prime mover such as are currently available; second, the weight ratio selected should be approximately consistent with the maximum capability which has been widely utilized with current helicopter configurations.

The sling configurations considered in this study were the three shown in Figure 106. Longitudinal stability was analyzed for the two-parallel-cable configuration (with cables 20 feet apart). Lateral directional stability was considered for all three major configurations illustrated in this figure. In all cases, the attachment points at the fuselage were on a level located 5 feet below the helicopter cg. Forward speed conditions of 40 knots and 140 knots were programmed on a digital computer, to study the relative dynamic stability characteristics with and without automatic stability augmentation systems (SAS), for cable lengths (H_0) of 10, 40, and 100 feet and also for internally located loads.

The longitudinal stability characteristics of the two-cable system with parallel cables ($d=D$) did not appear to be significantly different from those of the internally loaded helicopter. The basic SAS-on and SAS-off behavior of the combined system closely resembled that of the internally loaded helicopter of equivalent gross weight. This implies that the primary considerations in evaluating the relative importance of the various cable systems considered here must be the load aerodynamic behavior and the control capability afforded the pilot in controlling the motion of the load. A two- or four-cable suspension with parallel cables offers a significantly better load control capability than a single-cable suspension, because of the pitch coupling between the load and helicopter. At the same time, however, the aerodynamic forces on the load may exert undesirable forces on the combined system. A significant need exists for a rational tabulation of aerodynamically acceptable and nonacceptable loads which would serve as a guide to operations personnel engaged in external cargo-carrying missions. Most of the existing reports in this field are concerned with particular loads where the load aerodynamic characteristics have been well defined.

Some exception to these trends should be noted in the case of the high-speed longitudinal stability characteristics of an automatically stabilized helicopter utilizing SAS electrical circuits which effectively shape the feedback signals so as to account for the pitch acceleration feedback into the pitch control actuators. The possibility arises here that the cable spring characteristics may lead to uncomfortable SAS-induced pitch oscillation in the multi-cable suspension systems which may exhibit itself in a "pogo stick" effect in forward

flight. No experimental evidence appears to indicate such behavior, but should it occur, the stabilization devices may have to be redesigned. More investigation in this area is required, in order to define clearly the possibility of occurrence of such behavior and to optimize the stability augmentation parameters for heavy external-cargo-carrying helicopters.

The lateral directional stability of the multi-cable suspension systems shown in Figure 106 is primarily affected by the roll coupling between the helicopter and load resulting from the cable attachment point location below the cg level of the aircraft. In forward flight, location of the cable attachment point 5 feet, or thereabouts, below the cg level appears to be desirable, particularly with heavy loads and long cable lengths (40 feet or more). Since this is somewhat contrary to the optimum location for hovering flight, a trade-off study in this area may be desirable for a definition of the optimum overall performance. The suspension geometries investigated here indicate a slight suppression of the lateral directional instability in forward flight at high speeds (more than 100 knots) without the stability augmentation devices. A strong sideslip instability is introduced by the addition of the external load; stability deteriorates rapidly with forward speed. This tendency may be attributed to the absence of favorable aerodynamic characteristics of the heavy loads; it should, in principle, be considerably affected by the aerodynamic characteristics of the load - a subject beyond the scope of this study.

The general trends of this numerical investigation of the longitudinal and lateral directional stability modes associated with the suspension geometries shown in Figure 106 do not reveal many substantial differences in the trends of the dynamic stability from that of a single-cable configuration, except for the possible occurrence of the SAS-induced instabilities described for the multi-cable suspension, when the external loads are considered to have aerodynamically neutral stability. It would be reasonable to conclude at this point that an external load will influence the overall performance and speed limitations during external cargo-carrying missions more through its own aerodynamic stability characteristics and the resulting helicopter control trim and power requirements than through the basic suspension geometries considered here.

AIRLOAD EFFECTS ON SLINGS

External sling-load operations with modern, medium-sized helicopters revealed the existence of airflow-induced instabilities in the sling legs. Most of the slings currently in use are of the single- or multiple-ply nylon webbing variety. It is reasonable to assume that a 12- to 20-ton flying crane will normally use the same type of nylon web slings; consequently, the same instability phenomena will be experienced.

The significance of these aerodynamic instabilities on the mission effectiveness of a flying-crane-type helicopter can only be speculated. The main concern from a purely engineering viewpoint would be the remote possibility of eventual fatigue failure of the sling elements. From a practical point of view, the natural desire of aircrew personnel to avoid vibration, in spite of possible assurances that it is not detrimental, could lead to significant restrictions in the maximum mission speed of an operational crane.

The fact that sling instabilities have already occurred, and could become a factor in future crane mission effectiveness, more than justifies a cursory review of the subject.

Theory of Wind-Induced Oscillations in Slings

Qualitative information on a limited number of observed nylon sling instabilities is available. During these observations, one or more strands of the nylon sling began to oscillate or breathe at high frequency, transverse to the direction of the relative wind. The oscillations either began in hover and continued throughout forward flight, or began at some forward flight speed and were maintained at all higher speeds. Observers claimed that the frequency of oscillation increased with airspeed. The energy content was sufficient to be felt within the aircraft, when operating with heavy (over 10,000-pound) external loads.

In general, the phenomenon of aerodynamic instability is explained on the basis either of forced or of self-excited vibration. In the case of forced vibration, the impressed alternating force which excites the vibrations and sustains them exists independently of the resultant motion. This type of vibration is identified with vortex shedding and is characterized by small-amplitude high-frequency oscillations.

For self-excited vibration, the impressed alternating force is a function of the velocity of the resultant motion. This leads to a negative damping term in the equation of motion which, for a linear system, allows oscillations of increasing amplitude. Such vibration is usually of large amplitude and low frequency.

The occurrence of wind-induced oscillations in nylon webbing slings is explained by the Karman Vortex Trail. When a steady wind blows across certain long flexible elements under mechanical tension, vortices are detached on the downwind side of the elements. When an element is positioned to the relative wind in a so-called unstable orientation, the vortices are detached first from one side and then from the other, in a regular manner. Each vortex detachment is followed by a corresponding transverse force on the element. These forces, occurring in opposite directions and in a staggered regular or periodic manner, produce an alternating force.

The frequency of these wind-induced alternating forces has been shown to be

$$f = \frac{K \cdot v}{L'} \quad (15)$$

where

- f = frequency (cps)
- K = Strouhal number
- v = wind velocity or flight speed (ft/sec)
- L' = characteristic width of element (ft)

Strouhal number (K) is a basic constant of proportionality in problems of aerodynamic instability. It is normally a function of Reynolds number, but it can be taken equal to 0.2 for typical nylon sling webbings. For a given helicopter external sling, then, the forced vibration frequency (f) varies directly with forward flight speed (v).

For vibration analysis purposes, long flexible elements under tension (such as slings) are considered to be in the general class of the vibrating string. As such, their natural or resonant frequencies of transverse vibration can be established.

Theory yields the following equation for these resonant frequencies:

$$f_r = \frac{N}{2L_e} \cdot \frac{T_s \cdot g}{w_s} \quad (16)$$

where

f_r = resonant frequency (cps)
 N = any integer 1,2,3,...
 L_e = element length
 T_s = tension (lb)
 w_s = weight per unit length
 g = acceleration due to gravity

Thus, every external load sling leg has a series of discrete natural frequencies corresponding to the different values of N .

When the frequency of the wind-induced alternating force (f) coincides with one of these resonant frequencies (f_r), transverse vibration will occur at that resonant frequency. It would appear, then, that sling vibration would start and stop as airspeed was increased and as the discrete natural frequencies in turn were excited. Tests have shown that this is not quite correct. The linear theory has proved to be only approximate in nature, and the discrete natural frequencies have in many cases been quite close together. What happens in practice is that an element will vibrate at the nearest natural frequency, moving from one frequency to another as speed increases.

The control of aerodynamic instability is usually based on changes in physical constants of the system or the incorporation of some type of damping. In the case of helicopter external load slings, each of these methods presents formidable problems. The unique nature of each application and the dictates of criteria other than aerodynamic instability preclude the adaptation of most, if not all, of the classical solutions.

One practical solution to sling instability has been put forth by an experienced sling rigger, without recourse to the theory. This solution is to introduce twists into each leg of a multiple leg sling during sling-to-load attachment. With knowledge of this method of solution available, an attempt was made to justify it through theory.

Previously, reference was made to unstable orientation of a sling element. Nylon sling webbing normally has the form of

belting, with a width-to-thickness ratio on the order of 10 to 15. The sketch given below shows a typical sling webbing cross section positioned in both stable and unstable orientations relative to the wind.



The stable configuration is defined as that orientation which will not produce the vortex shedding required for aerodynamic instability. The unstable orientation will result in vortices being shed alternately from Points A and B, thus producing the instability. The twisting of sling legs will produce an element with stable, unstable and all intermediate orientations, independent of the direction of the wind. This reduces the maximum length of element which can be in an unstable orientation at any given time. In addition, for each one-half turn of leg twist (T_s), the overall length of the element (L_e) is divided into vibrating segments of reduced length L_e/T_s . When the reduced lengths are used in Equation 16, they have the effect of raising the resonant frequencies. When sling leg twists of the proper number are incorporated, a sling leg can, theoretically, be made free from aerodynamic instability up to some maximum airspeed.

Using reasonable values for the parameters of Equation 16, it appears that sling leg twisting offers a solution up to an airspeed of about 120 knots.

Conclusions and Possible Future Efforts

Within the speed range presently envisioned for the 12- to 20-ton flying crane (90 to 110 knots), it appears that present types of nylon webbing slings can be rigged so as to avoid aerodynamic instabilities. It should be remembered that the simplified analysis presented herein is based on observer comments rather than on actual measured data and basic linear theory. The analysis neglects possible flutter, stall flutter, buffet, and other nonlinear effects which may be present. A more detailed analysis was not considered necessary at this time because of the rather small influence of this phenomenon at present.

The ground work has been laid for future analyses, in case airload effects on slings do become a serious problem. Any significant increase in cruise speed with external loads will dictate further study in this area.

TEST PLAN

INTRODUCTION

The objective of the test plan is to describe procedures, equipment and associated items required in the experimental testing necessary to quantify and qualify the design parameters defined in the preceding sections of this report. Two items which will be conducive to the attainment of this objective are the introduction of the two-point suspension and hoist system and the optimization of helicopter stability and control for the external load mission.

A program for the developmental testing of slings has already been funded by the Air Force; a review of the progress to date indicates that the program is adequate for near-term requirements. An extended development program should be funded which would ensure sling configurations that will satisfy proposed heavy-lift helicopter requirements.

Development and testing of the four-point hoist system is assumed to be already contracted for. Since detail design information on the CH-54A subsystems is not available to The Boeing Company, a test program will not be presented.

Winch, cable, cargo hook, and associated equipment technology has remained nearly static for the past decade; consequently, further study of these items and associated subsystems is indicated and should be initiated. The objective of additional study would be to originate military specifications for hoist equipment procurement; emphasis should point toward more realistic qualification testing.

PROPOSED TEST PLAN FOR TWO-POINT SUSPENSION EVALUATION

Objectives

To permit a comparative evaluation of a two-point system with the four-point system currently being evaluated on the CH-54A helicopter, construction of the two-point system described below is proposed. Test objectives would be the evolution of an external system of transporting cargo by helicopter which will achieve the following:

1. Offer greater simplicity compared with the existing four-point system
2. Reduce hookup and discharge time
3. Provide electrical and manual load release by the pilot, without the use of devices which cut the cables
4. Achieve maximum system productivity
5. Eliminate the need for a single-point hoist system.

Description of the Proposed Two-Point Suspension System

The two-point suspension system will consist of a beam to which will be secured two or more cargo hooks of a type currently in the Army inventory. The equipped beam will be suspended by cables from existing hard points located on the CH-54A helicopter. Support cables will be designed in such a manner that the vertical distance between the beam and the underside of the fuselage can be adjusted with the helicopter on the ground, in 10-foot increments. Refer to Figure 108.

After flight testing, the suspension system will be modified into a two-point hoist system. To utilize existing hardware (i.e., winches), it is proposed to suspend the beam from two winches as shown in Figure 109. Winches proposed for the modification are presently under evaluation on the CH-54A four-point hoist system. Although only two winches will be used, hoist system capacity will be maintained by reeving each cable system as shown in Figure 109; the resulting rate of the system will be halved.

For purposes of this test, winch system synchronization is not considered to be necessary, but independent control of the winches will be required. Lift synchronization will be the responsibility of the third pilot or crane operator. To compensate for beam rise and fall, the electrical conductors used for hook release will be provided with a constant-tension device (e.g., a negator-type spring reel), as described later in this section. Emergency release of the hoist system during evaluation testing will be accomplished by cable cutters already embodied on the winches.

Note: For subsequent operational systems, a manual system override must be placed in parallel with the electrical control system.

Instrumentation

For flight testing, it is recommended that load cells be installed in the suspension lines to monitor the load distribution.

Proposed Flight Test Program

A flight test program is proposed as follows:

1. Initially, the two-point suspension system (refer to Figure 108) will be installed approximately 5 feet under the fuselage bottom, and cargo hooks will be evenly loaded with high-density palletized test loads.
2. After lift-off, hover, and transition into forward flight, flight speed will be increased in 10-knot increments up to maximum cruise speed. Turns of 180 degrees will be performed, the rate of turn being progressively increased to the maximum allowable for the aircraft.
3. Items 1 and 2 will be repeated with the high-density palletized loads replaced by loads known to be unstable; for example, long blade boxes or telephone poles.
4. The above tests will be repeated with the suspension length increased to 20 feet. Pickup of the load will be accomplished with the helicopter in hover attitude.

5. On completion of Item 4, above, the two-point suspension will be replaced by the two-point hoist system shown on Figure 109.
6. Loads will be picked up with the two-point hoist system from hover at heights varying from 10 feet to the limit of hoist-system cable length. Flight tests will be conducted as in Item 2. Additionally, the load, after pickup, may be hoisted to the aircraft during transition to forward flight. The reverse transition procedure will be executed on the aircraft's approach to the landing zone.
7. Flight tests described in Items 1 through 6 will be repeated, with vehicles suspended as cargo.
8. Upon completion of the aforementioned tests, the two-point hoist system will be evaluated for single-point lift capability. The proposed arrangement is illustrated in Figure 110. The proposed pickup procedure will be to lower the two-point system to its maximum cable length of approximately 75 feet and then to pick up the load on the single hook suspended by twin cables from the slung beam. Upon hoisting the load to the aircraft, it is anticipated that a degree of torsional restraint will exist which is comparable to that now obtained by the use of cargo sling systems. Refer to the LOAD SUSPENSION SYSTEMS section.

Sequential Procedure for Evaluation and Development of a Two-Point Hoist System

The following sequential procedure will be used:

1. System design and fabrication.
2. Modification to the CH-54A helicopter. The changes required will be minor; existing hard points will be used. Under the assumption that the test vehicle will be one modified for the four-point hoist system, the hydraulic system changes will already exist, and only small extensions to the flexible hydraulic hose will be necessary.

3. The addition of a constant-tension-type stowage reel for the electrical conductors used in hook release will be required. Preliminary investigation indicates that these items are available as off-the-shelf equipment (refer to Figure 111).
4. Existing winches will be used (refer to Figure 49). A modification to the cable termination similar to that shown in Figure 109 may be required, although it appears feasible to use the hook termination as designed. Winches will be mounted on the helicopter by means of universal joints secured to existing hard points on the helicopter fuselage.
5. System limitations (prime mover) must be obtained from the helicopter manufacturer.
6. Load cells, if fitted, must be calibrated.
7. Flight test of the two-point suspension system.
8. Change the system to a two-point hoist system.
9. Ground checkout of the system.
10. Flight test of the two-point hoist system.
11. Flight test of the single-point lift. The hook used may be that currently used on the CH-54A single-point hoist system.
12. Compare results with the four-point hoist system results.
13. Assuming that the two-point hoist system achieves its design objectives, prepare specifications for an operational system.
14. Procure and qualify the operational system.
15. Aircraft retrofit.

Note: The configuration proposed was evolved to utilize existing hardware, and to keep costs at a minimum during the evaluation of two-point systems. The optimum installation would be more in line with that shown in Figure 112.

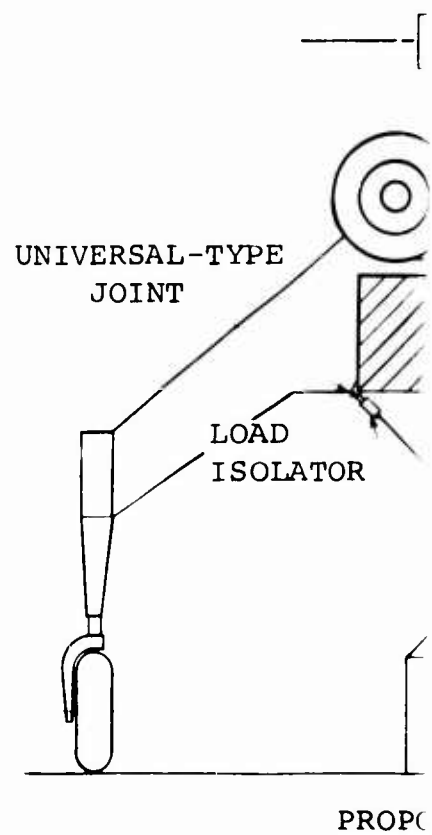
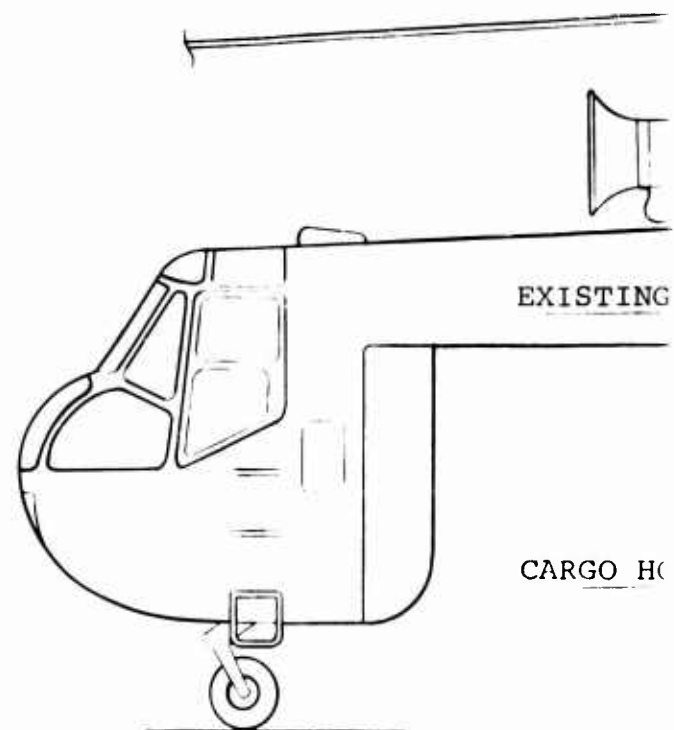
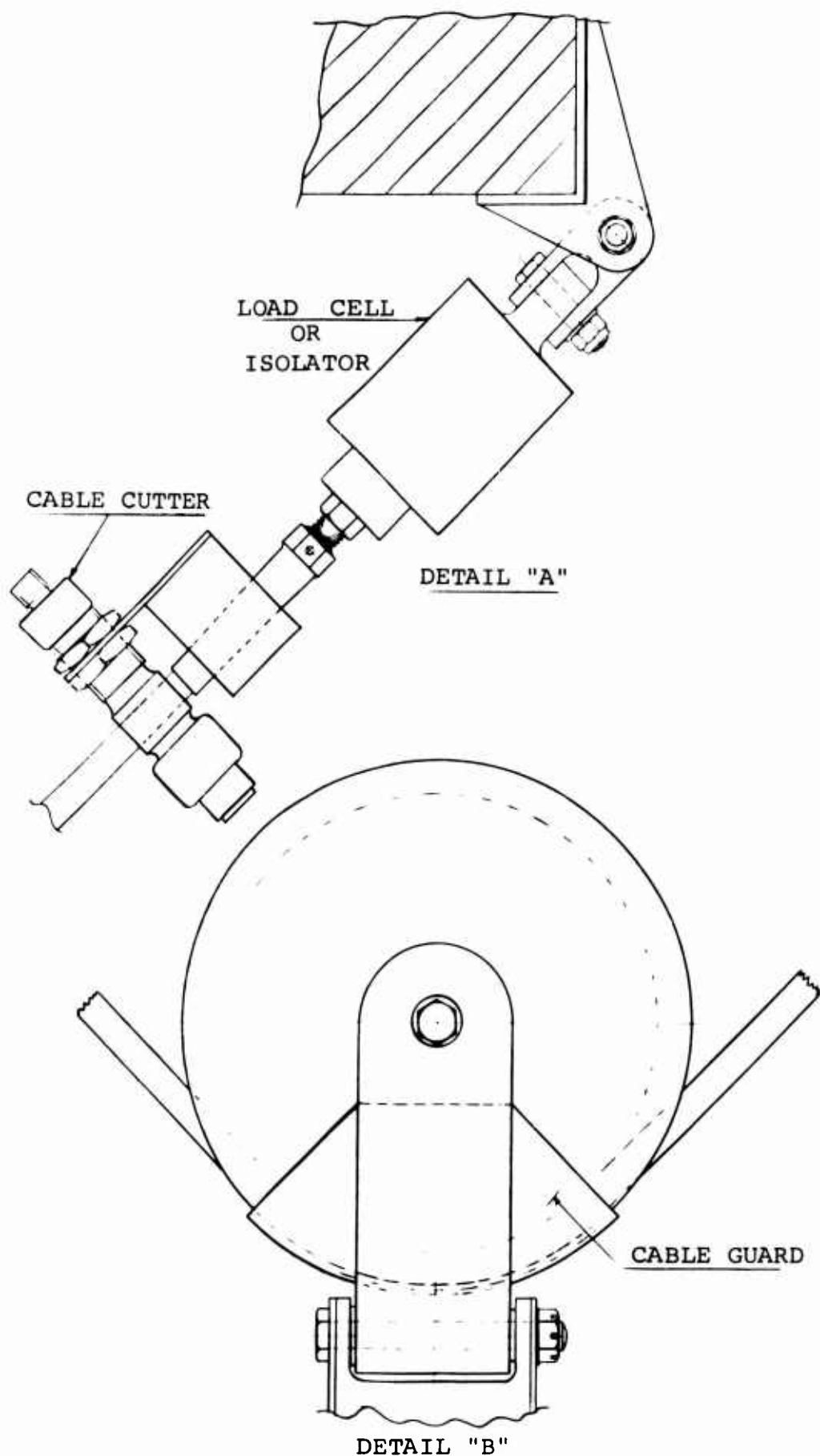
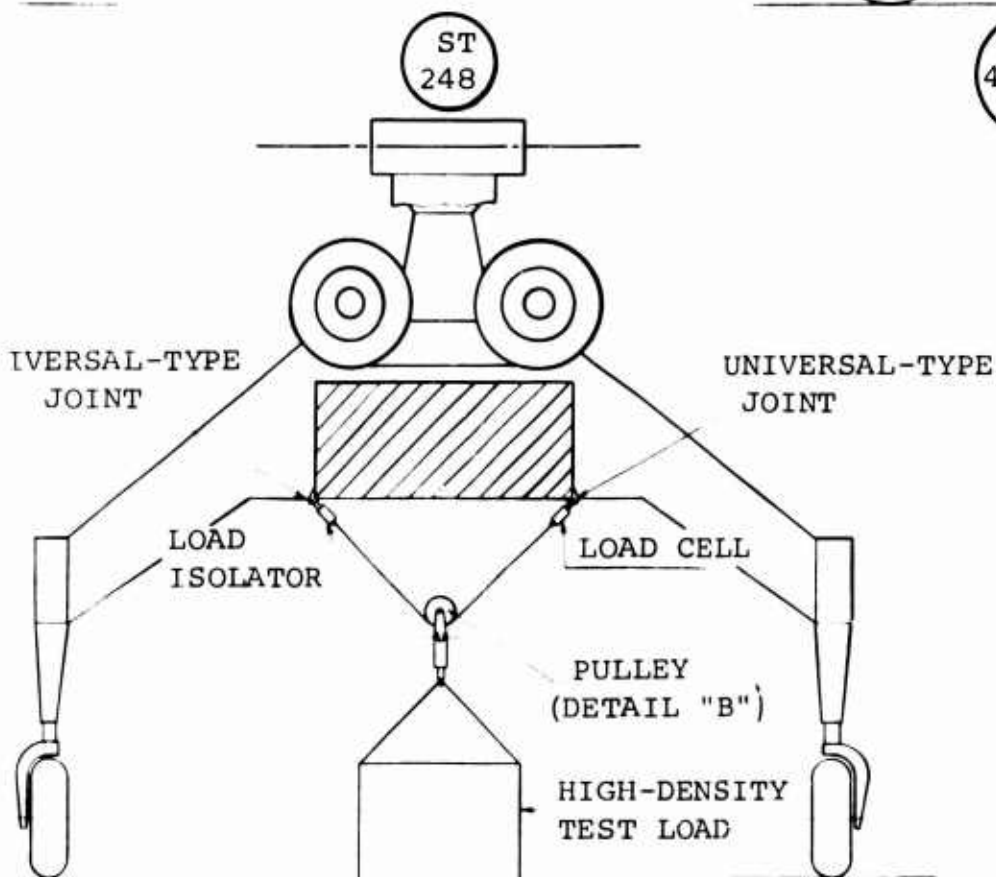
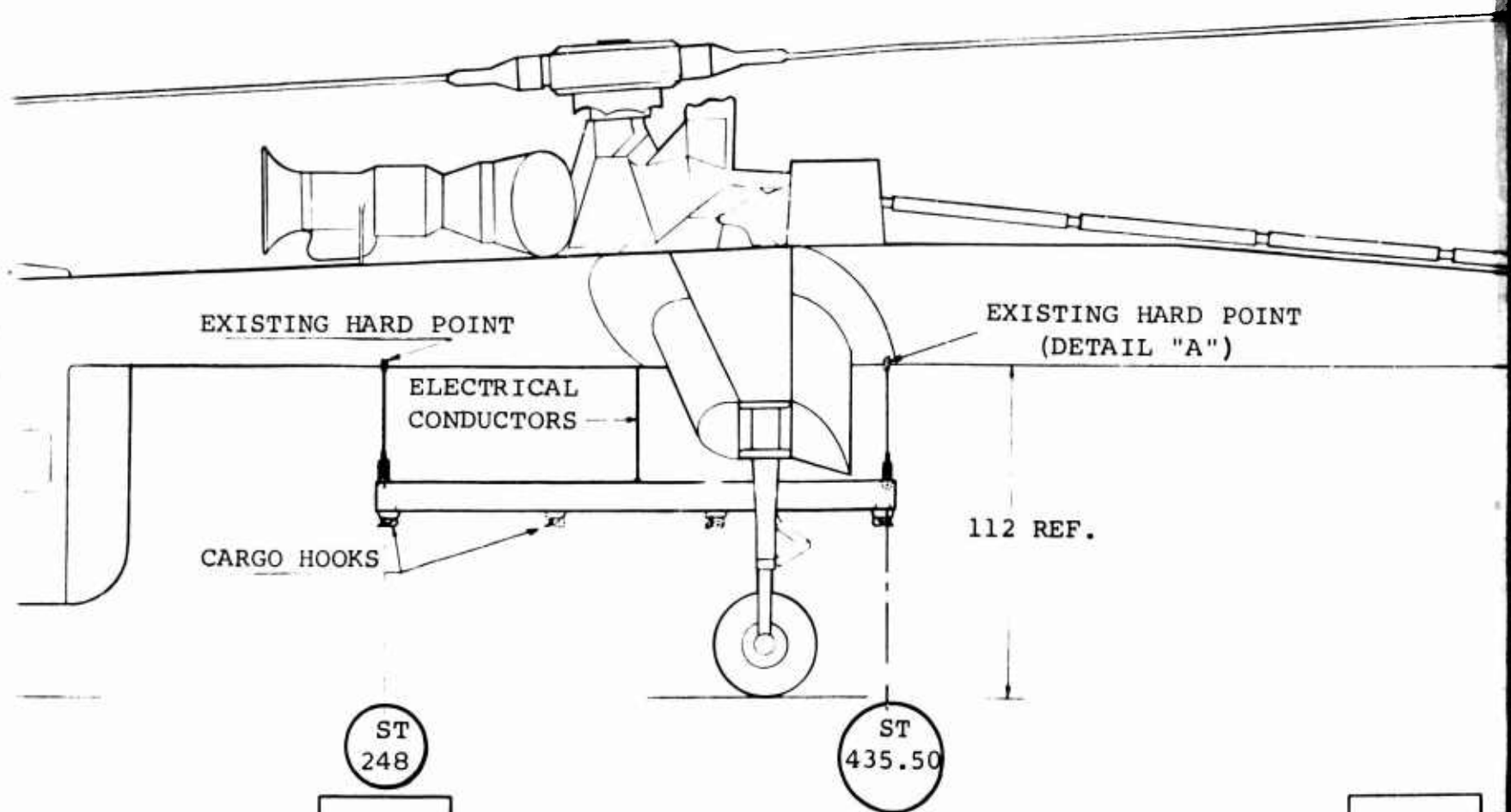
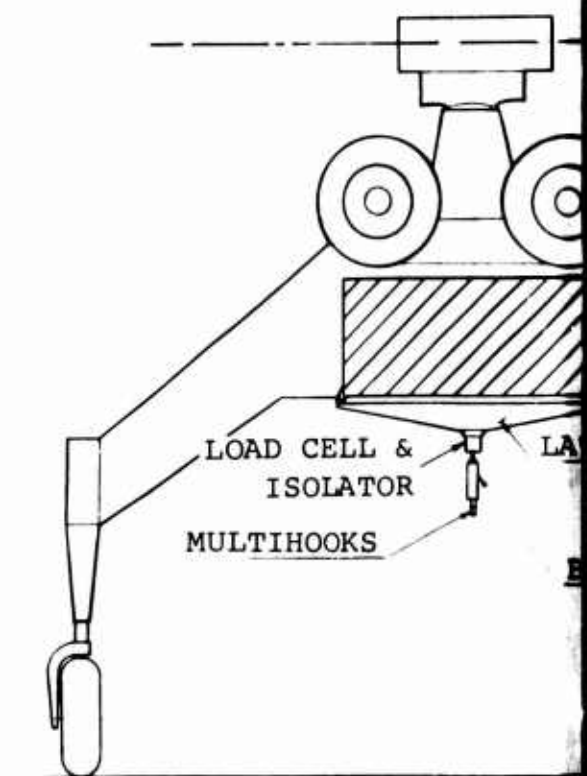


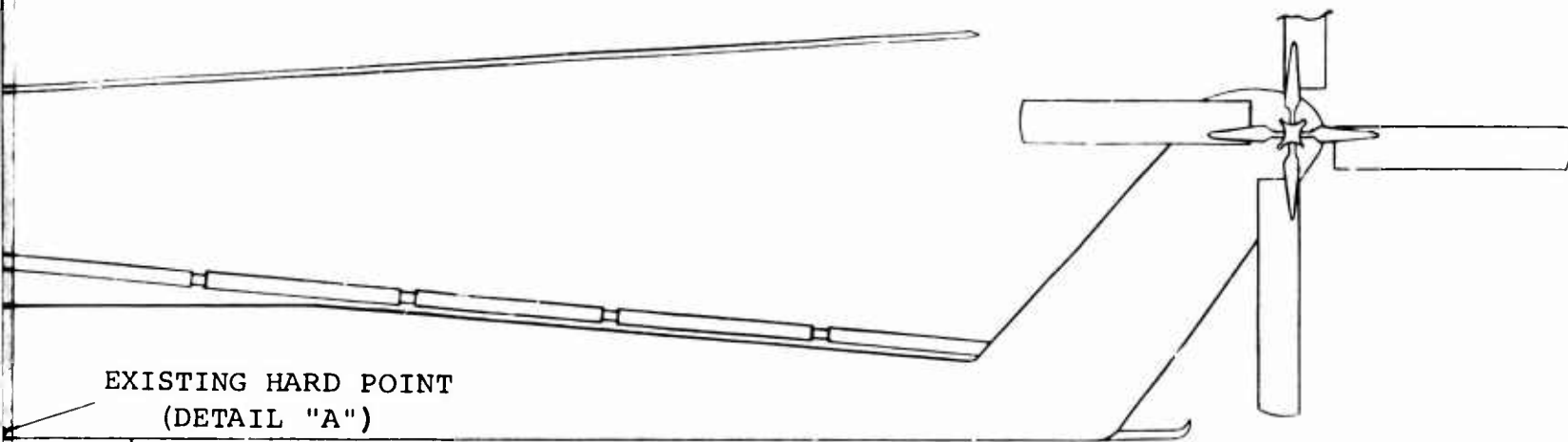
Figure 108. Proposed Two-Point Suspension System



PROPOSED METHOD

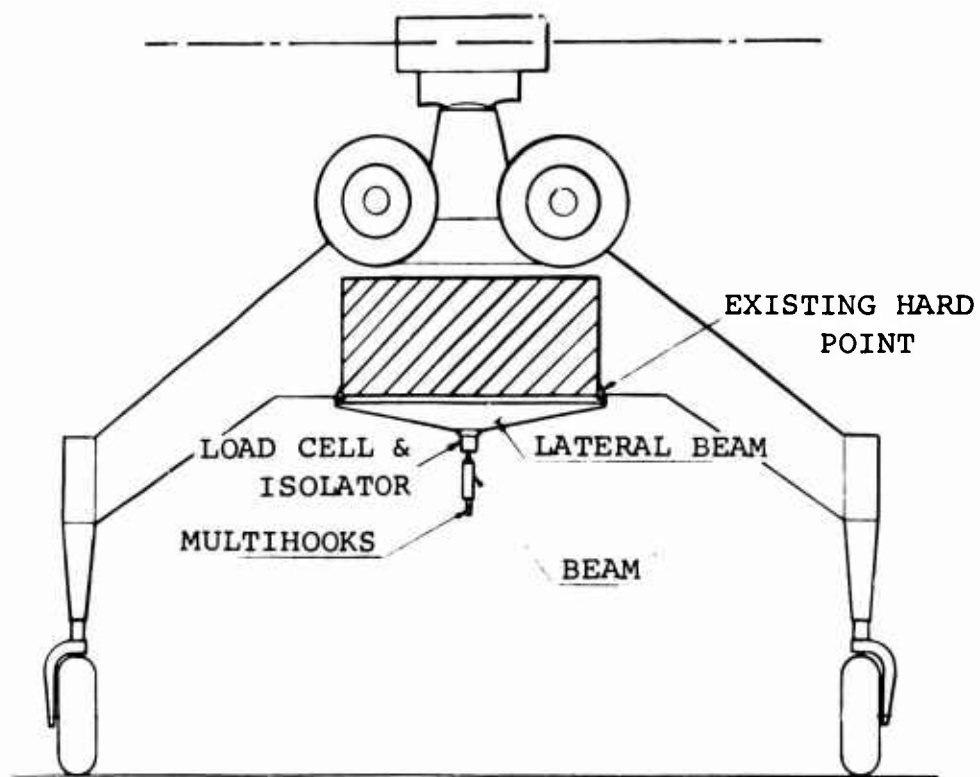


ALTERNATE METHOD

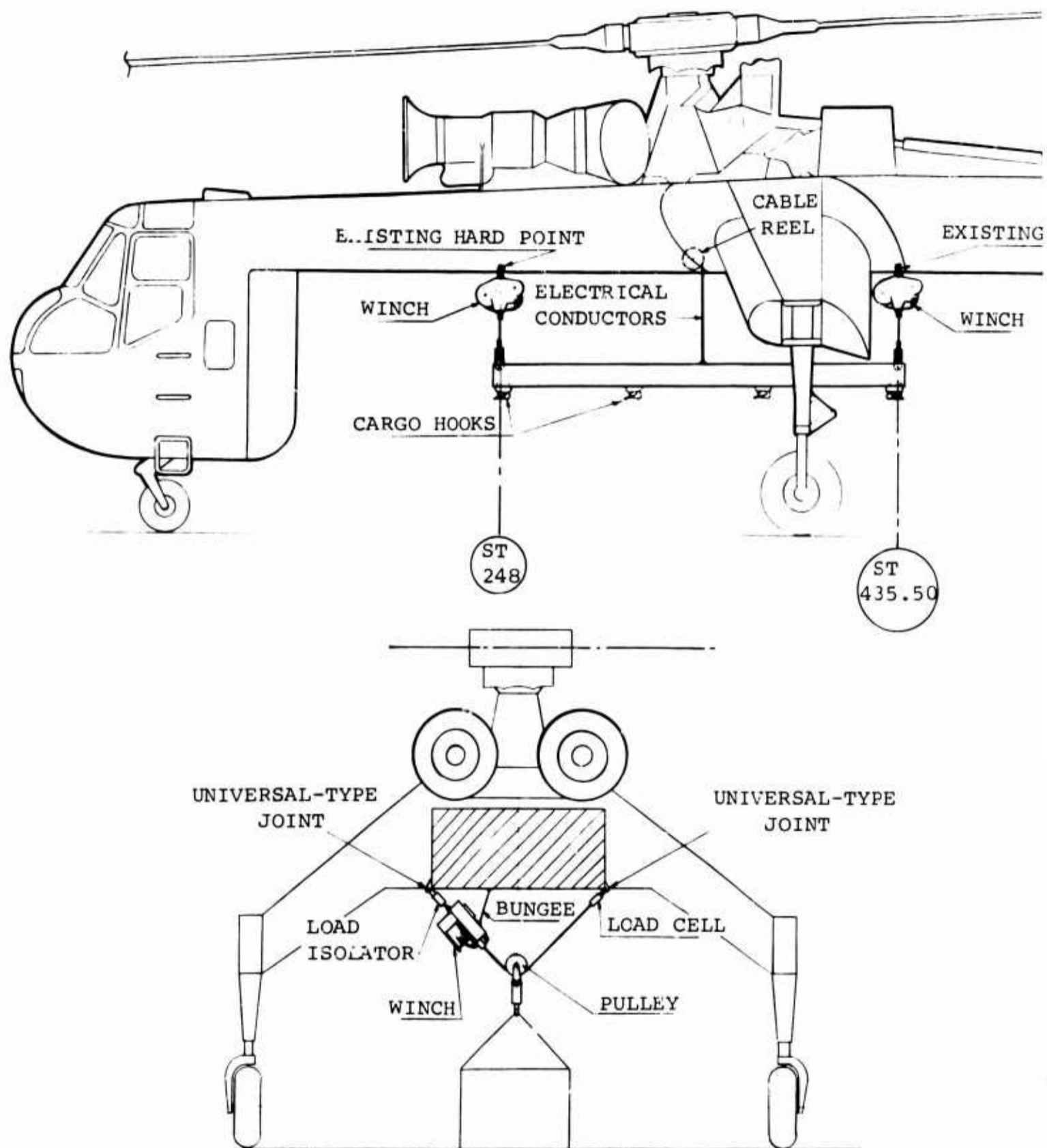


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ALTERNATE METHOD



PROPOSED METHOD

Figure 109. Proposed Two-Point Hoist System

A

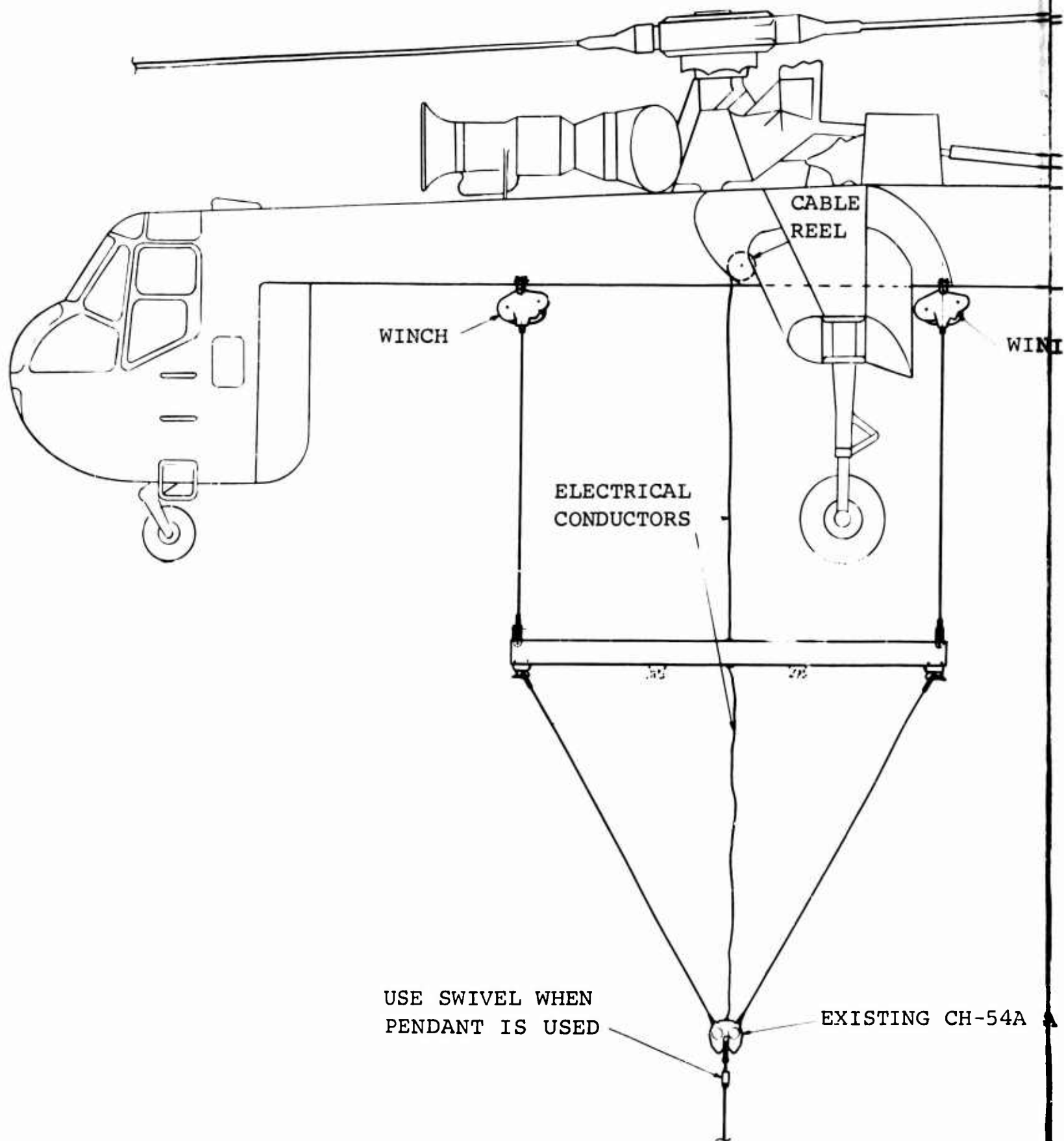
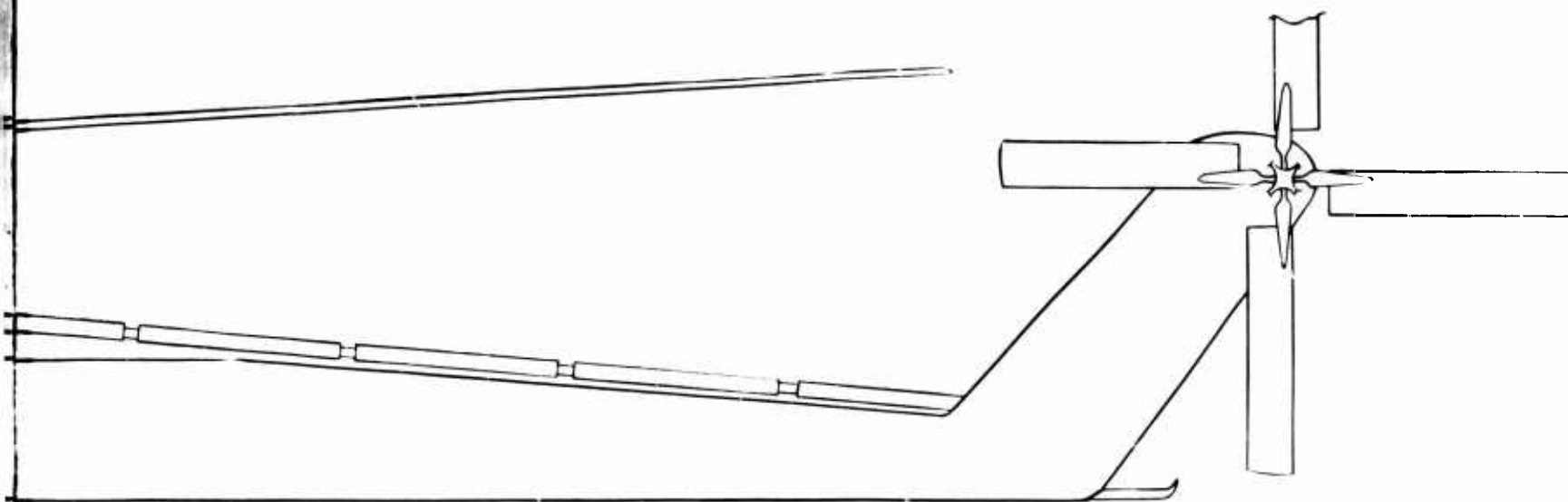


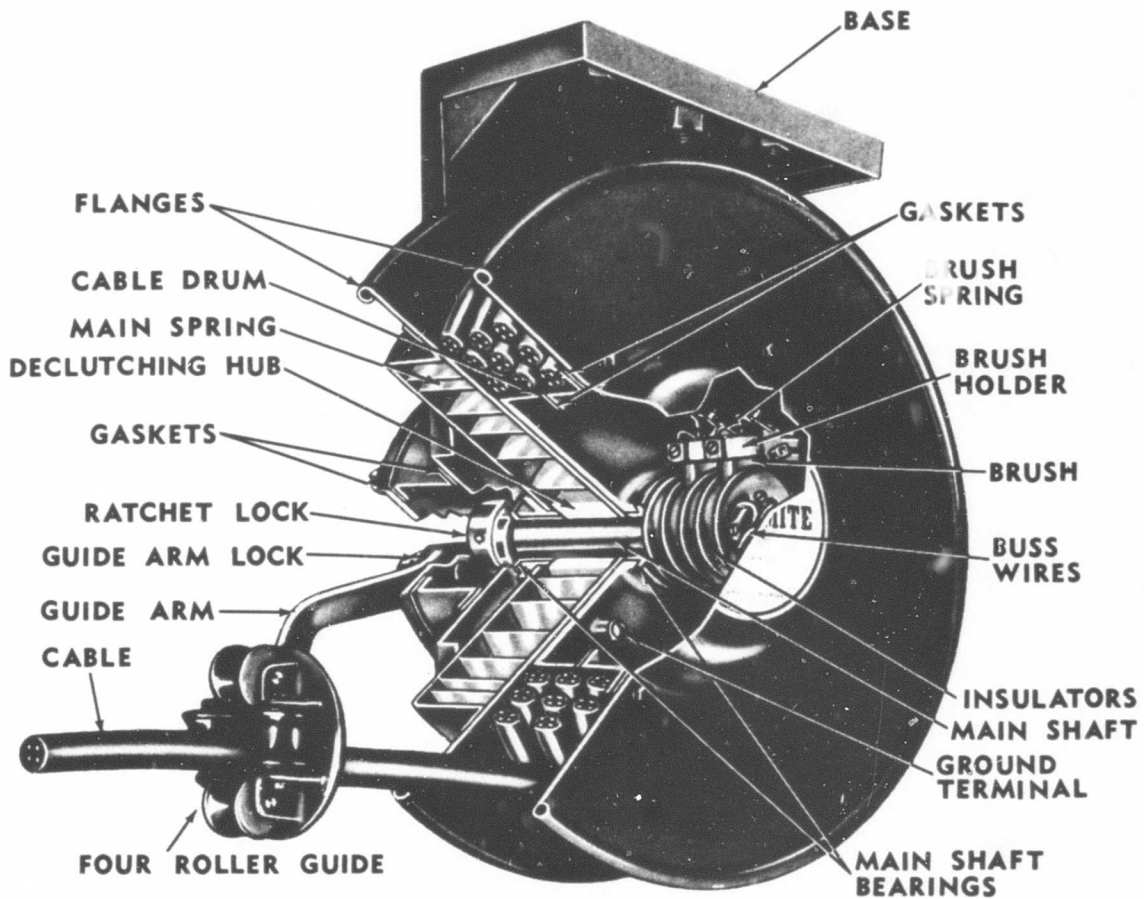
Figure 110. Proposed Single-Point Lift With Two-Point System



INCH

A SINGLE-POINT HOOK

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Aero-Motive Manufacturing Company

Figure 111. Constant-Tension Cable Reel

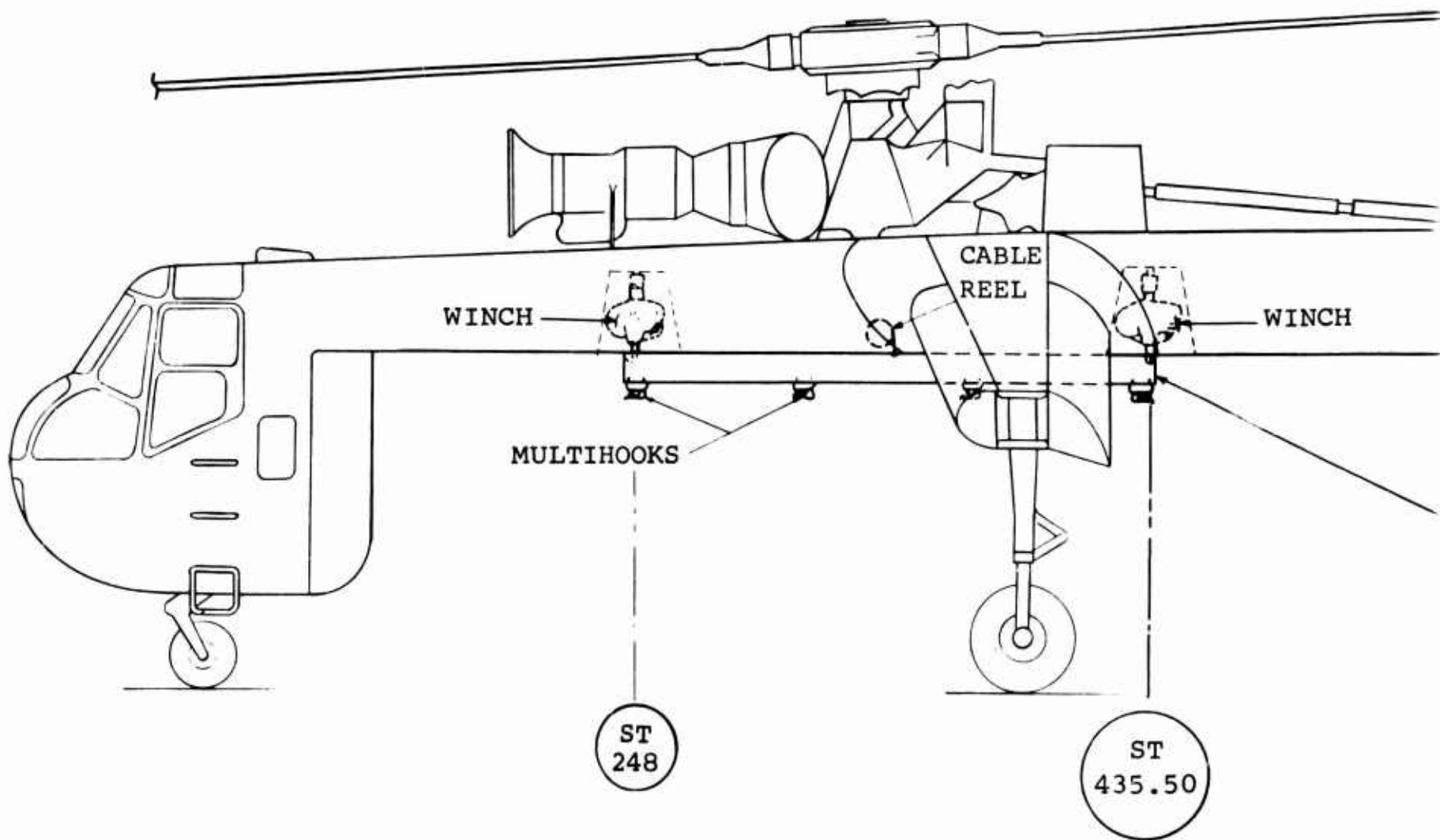
Load Aerodynamic Stability

The analysis described in the LOAD SUSPENSION SYSTEMS section under the heading STABILITY OF SLUNG LOADS (page 32) indicates that the primary reason for adopting multi-point suspension is to provide a restraining torque to resist load yaw motion, thus increasing the stable speed range of the load. Analysis of helicopter forward flight stability shows that the helicopter basic stability is not much affected by an external load and that speed limitations are usually due to aerodynamic instability of the load causing undesirable helicopter motions.

Since most typical loads are aerodynamically unstable in yaw, a mechanical restraining device, such as a multi-point suspension, may be used to raise the speed at which instability occurs to an acceptable level. However, the amount of restraining moment is limited by the maximum practical suspension separation. The use of long suspensions further reduces the available restoring moment. Another approach to increasing the speed capability of the load is to reduce its aerodynamic upsetting moment or, if possible, to make it aerodynamically stable in yaw. This may be accomplished by the addition of a vertical stabilizer surface to the load. Naturally, it is undesirable to add such complexity to each and every unstable load; however, when using a two-point suspension with a connecting beam, the stabilizer surface may be fitted to the beam.

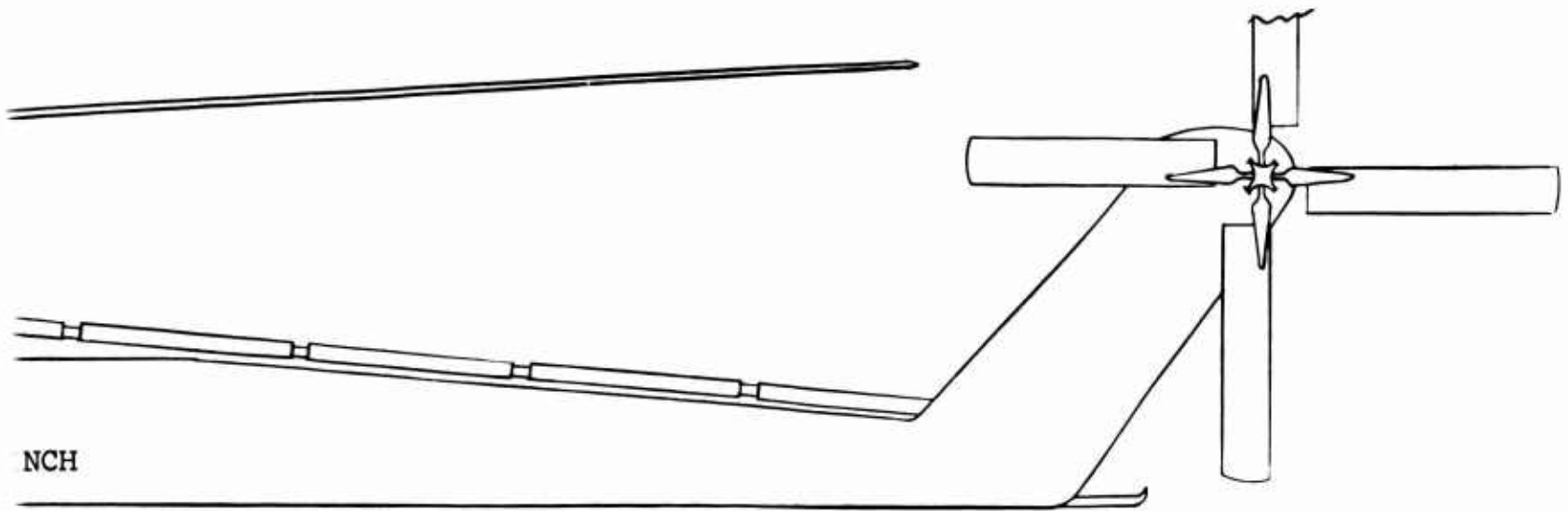
For evaluation purposes, the vertical stabilizer may be constructed by using typical aircraft flying-surface practice; it may then be fitted to an aft extension of the beam. For operational applications of such a device, the stabilizer might take the form of an inflatable surface which could be simply folded into the rear of the beam. Such structures have been adequately demonstrated by the Goodyear Aerospace Corporation in their inflatable aircraft. The advantage of using a stowable stabilizer is that it could be stowed during operations in which it is necessary to winch the beam up to the fuselage and to engage supplementary locks.

It is recommended that a stabilizer be designed and built to a size to be determined by a study of typical Army loads. It is recommended that highly unstable loads be used for this phase of testing (those used for Item 3 of the flight test program would be suitable). The stabilizer should be fitted to the two-point suspension beam as described above, and the

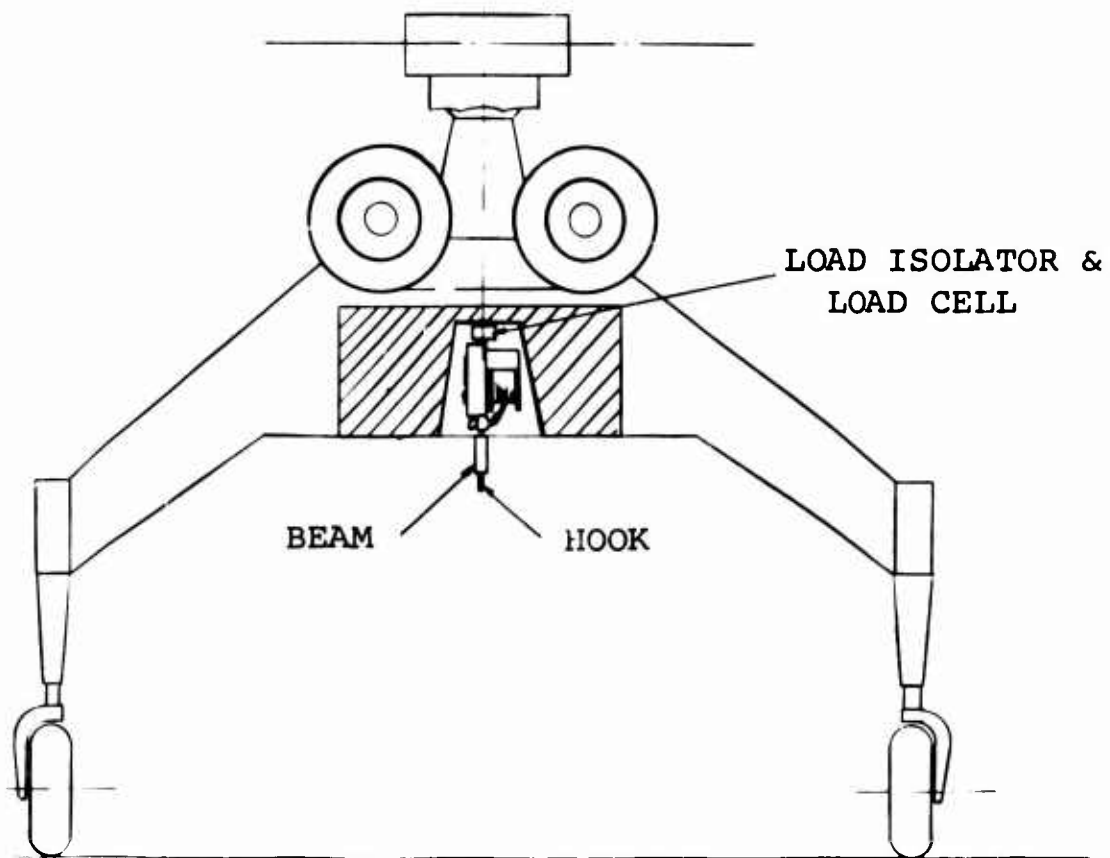


A

Figure 112. Proposed Operational Two-Point Hoist System



BEAM LOCKS TO STRUCTURE
TO UNLOAD WINCHES



OPERATIONAL SYSTEM

flight tests with long suspension should be repeated. Comparison of maximum safe speeds should indicate the desirability of the stabilizer system, but consideration must be given to the effect of maximum speeds of approximately 160 knots - expected of future heavy-lift helicopters - in comparison with the effects of the 110-knot maximum available from the CH-54A for actual testing.

VERTICAL BOUNCE

Objective

The objective of this portion of the proposed test plan is to qualify and quantify methods of controlling the vertical bounce phenomenon in external load-carrying helicopters.

Discussion

The analysis described in the section entitled EFFECTS OF EXTERNAL LOADS ON HELICOPTER HANDLING, STABILITY, AND VIBRATION identified the vertical bounce problem as an instability caused by inadvertent control inputs by the pilot. The problem is accentuated by the addition of an external load tuned to bounce or vibrate vertically at a frequency close to the instability - typically 3 to 4 cycles per second. Methods of controlling the vertical bounce phenomenon may be divided into two classes: (1) devices added to the suspension system to lower the load bounce frequency below the instability range (load isolators) and (2) techniques to modify the pilot's inputs to the control loop in order to minimize the effect of specific inadvertent control perturbation.

A substantial amount of investigation and flight tests concerning the vertical bounce phenomenon has been funded by the Air Force and performed by Vertol Division on the Army CH-47A Chinook. This program included instrumented flight test with different payloads and sling stiffnesses. Other factors investigated were friction stick dampers and orifice-type stick dampers. Initial results from this program, which is due to be completed in July 1966, were used in substantiation of the vertical bounce analytical study described earlier in this report.

It is recommended that the investigation and flight test of methods for controlling the vertical bounce problem be performed on a CH-47A, since the experience gained in the above-mentioned contract provides substantial background and will save time and dollars. The results of the investigation would be equally applicable to the CH-54A and to future heavy-lift helicopters.

Possible methods of resolving vertical bounce problems are discussed under the separate categories of Load Isolators and Modifications to Thrust Control Systems in the following paragraphs.

Load Isolators

The CH-54A load isolator is of the liquid-spring type, similar to a landing gear shock strut. In such a system, the bounce frequency is a function of the applied load. Army CH-54A pilots indicate that the load isolator has not completely solved the bounce problem (refer to SINGLE-POINT SUSPENSION, page 16, in the LOAD SUSPENSION SYSTEMS section). Although details of the CH-54A load isolator are not available to the writers of this report, it is felt that the problem may be due to the change of frequency with load; for this reason it is suggested that variable-pressure, constant-height, or self-adaptive airsprings be investigated.

Self-adaptive airsprings, as fitted to the suspension systems of trucks and buses, exhibit substantially constant load bounce frequency with varying load. To achieve this, it is necessary to provide the airspring with a supply of pressurized air and a valve which adjusts the standing height of the spring to approximately midstroke. This is accomplished by adding air to, or bleeding air from, the airspring.

The spring rate of such a device depends upon the piston area and air volume so that, for a given airspring, the spring rate may be changed by altering the air volume. For a flight test program, the change in spring rate may be accomplished by using a variety of commercial air bottles connected to the airspring through an electrically controlled selector valve, so that the pilot may change the suspension frequency in flight. The airspring and leveling valve may be modified automotive units. Compressed air may be supplied either from a pre-charged high-pressure accumulator or from engine compressor bleed.

Modifications to Thrust Control Systems

The required effect when modifying the thrust control system for minimization of vertical bounce is to filter out inadvertent 3-4-cycle-per-second pilot inputs to the control system. This must be accomplished without impairing the pilot's ability to perform the normal control functions, particularly in the external load mission, where the ability to hold a hover position with precision is of utmost importance. Several approaches to this problem are described below:

1. Thrust Stick Damping - Stick dampers are added to effect an increased impedance to high-frequency inputs; they are commonly fitted to control systems. For the external load mission, it has been found that increased stick damping helps to control the vertical bounce phenomenon; however, no data exist on the optimum damper to give a balance between high stick impedance and adequate control sensitivity. It is recommended that friction, viscous, orifice, and rate-limited orifice dampers of varying rate be evaluated in flight testing of a helicopter with and without an external load, in order to determine if a damper can satisfy requirements in both modes of flight.
2. Change in Thrust Control Gain - Analysis of the vertical bounce phenomenon indicates that a reduction in thrust control gain can eliminate the problem. There are various ways to reduce gain, but the overriding problem is one of maintaining sufficient total control travel. For this reason, a simple total reduction of gain is not feasible. It is necessary to introduce a reduced gain for small displacements of the stick about any intermediate trim position. The difficulty then is in reducing the effective gain sufficiently to eliminate the vertical bounce problem while maintaining sufficient control sensitivity. It is recommended that techniques to effect a reduced thrust control gain be studied and flight tests be performed to determine the feasibility of such systems.
3. Change in Thrust Stick Mass and CG - Study of the effect of thrust stick mass and cg indicated that it is normal to design the stick with an effective cg ahead of the pivot. This results in a positive g

feel in the stick - a characteristic pilots claim is desirable. However, experience with fixed-wing aircraft has demonstrated that while the positive g feel characteristic is desirable, it is by no means essential to the pilot's control of the aircraft. Typically, in fixed-wing aircraft, the lateral control static stability (spiral stability) is sacrificed for positive dynamic (Dutch roll) stability. In the case of the helicopter, therefore, it may be found that elimination of positive g feel by providing an aft stick cg might result in a stabilization of the vertical bounce phenomenon, while not seriously affecting the handling qualities. It is recommended that further study and flight testing be performed to evaluate the effect of thrust stick aft cg on the vertical bounce phenomenon.

4. Change in Thrust Control Mode - The essential mechanism in the vertical bounce phenomenon is the coupling of vertical fuselage and pilot motions through the vertically traveling thrust control stick. If the thrust control was a fore-and-aft-moving throttle-type lever, as in the Hawker 1127 VTOL, the coupling between vertical pilot motions and thrust control and, hence, vertical bounce would be minimized.

There is some controversy on the question of ease of transition from a collective-pitch-type lever to a throttle-quadrant type and, also, on the degree of control sensitivity achievable when using the throttle type. The Air Force specification in HIAD requires both types to be fitted to all new VTOL aircraft. From a study of published pilots' comments on most of the modern VTOL aircraft, the consensus seems to be that, for an aircraft which spends a minimum amount of time in hover, the throttle quadrant is best. Where a substantial amount of precise hovering is necessary, the collective-pitch-type lever is preferred.

It is recommended that the application of the throttle-quadrant-type thrust control be evaluated for the external load-carrying helicopter in order to ascertain whether the control sensitivity is adequate for the load acquisition portion of flight. For

flight test evaluation, the collective control may be activated electrically via the servo system.

CONCLUSIONS

1. The present development into the four-point winched suspension system on the CH-54A may present problems of hoist and hook release synchronization, the solutions to which could be complex.
2. A two-point hoist system satisfies the load restraint requirements that dictated the four-point system and shows promise of achieving hoist and hook release synchronization by relatively simple means.

It should be noted, however, that if extra precautions are required in the external transportation of high-value items, a rigid four-point system with effective redundancy could be developed which may prove effective in retaining the load in the event of partial system failure.

3. Two separate winched-type systems, single-point and multi-point, are logistically unsound within the same subsystem. Investigation reveals that elimination of the single-point winch could be accomplished without losing single-point hoist capability.
4. A 20-ton-capacity airborne winch is considered to be unacceptable from a size and weight point of view, unless a breakthrough in cable technology occurs.
5. No facility exists for the qualification of airborne hoist systems now being introduced or proposed for future use.
6. Significant gains have been realized in the development of slings and nets over recent years. Further programs oriented to provide slings for future heavy-lift requirements should be initiated.
7. Pods and platforms are effective in transporting bulk loads, provided there is sufficient volume of compatible loads to justify procurement of an aircraft type specifically designed to use them.

8. Analysis of the vertical bounce phenomenon indicates that, with sling loads, an unstable condition may result when the pilot is in the control loop with an unmodified response between cockpit control displacement and rotor control motion. This problem may be solved by using a load isolator in series with the sling load, or by making modifications to the thrust control system.

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13. ABSTRACT <p>This report covers an investigation into the mechanics of handling external cargo by helicopters. It comprises an analytical study of airborne hoist systems and comparisons of load acquisition techniques, crane-type long landing gears, and single- and multi-point suspension systems.</p> <p>The vertical bounce phenomenon is analyzed in detail and found to be dependent on inputs to the thrust control system provided by the pilot. The stability of the helicopter in forward flight is analyzed for neutrally stable slung loads. Forward-speed stability and control limits are usually the result of the effects of load aerodynamic instability on the handling qualities of the helicopter.</p> <p>For aerodynamically unstable loads, multi-point suspension allows a significant increase in forward speed over single-point suspension.</p> <p>A test plan describing equipment and associated items required to quantify and qualify the defined design parameters is included.</p>		

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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